THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Decarbonization of construction supply chains

Achieving net-zero carbon emissions in the supply chains linked to the construction of buildings and transport infrastructure

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Department of Space Earth and Environment

CHALMERS

UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2020

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Printed by Chalmers Reproservice

Gothenburg, Sweden 2020

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Abstract

Sweden has committed to reducing greenhouse gas (GHG) emissions to a net-zero level by Year 2045. In Sweden, about 20% of its annual CO_2 emissions are from the manufacture, transport and processing of materials for both the construction and refurbishment of buildings and transport infrastructure. Cement and steel, together with diesel use in construction processes and material transport account for the majority of the CO_2 emissions associated with building and infrastructure construction.

This thesis assesses the challenges associated with reducing CO_2 emissions from the supply chains for buildings and transport infrastructure construction. The main aim is to determine the extent to which abatement technologies across the supply chain can reduce the GHG emissions associated with construction if combined to exploit their full potential, while identifying key barriers towards their implementation.

The work takes its starting point from material, energy and emissions flow analyses conducted across the construction supply chain, followed by the development of stylized models, which are subsequently used for scenario analysis. This quantitative analysis work is integrated with a participatory process that involves relevant stakeholders in the assessment process. The participatory process serves to identify the main abatement options, as well as to adjust decisions and assumptions regarding abatement portfolios and timelines, so as to make these as realistic and feasible as possible. Supported by a comprehensive literature review, a detailed inventory of abatement options in the supply chain of building and transport infrastructure construction is developed. This includes technologies and practices that are currently available and that are deemed available on a timescale up to Year 2045.

The results show that on a national level, it is possible to reduce GHG emissions associated with the construction of buildings and transport infrastructure by 50% up to Year 2030, through applying already available measures. Moreover, it will be feasible to reach close-to-zero emissions by Year 2045, with this requiring comprehensive measures across-the-board, including breakthrough technologies for heavy vehicles, cement and steel production. Attaining the full abatement potential of measures that are already available would rely on sufficient availability of sustainably produced second-generation biofuels, requiring accelerated implementation of alternative abatement measures, involving optimization of material use, mass handling and transport systems, as well as the use of alternative materials and designs, with focus on circularity and material efficiency measures. To realize the potential linked to applying measures across the supply chain, there is a need for extensive collaboration along the whole value chain. Policy measures and procurement strategies should be aligned to support these measures with a clear supply chain focus, so as to enable balanced risk sharing and the involvement of contractors early in the planning and design process.

The results also illustrate the importance of intensifying efforts to identify and manage both soft and hard barriers to implementation and the importance of acting promptly to implement available measures (e.g., material efficiency, recycling and material/fuel substitution measures) while actively planning for long-term measures (electrification of heavy vehicles and low-CO_2 steel or cement). There are immediate and clear needs to prepare for deeper abatement and associated transformative shifts and to consider carefully the pathway towards these goals while avoiding pitfalls along the way, such as an over-reliance on biofuels or cost optimizations that cannot be scaled up to the levels required to reach deep emissions reductions.

Therefore, strategic planning must be initiated as early as possible, as lead times related to planning, securing permits and construction of the support infrastructure (renewable electricity supply, electricity grid expansion, hydrogen storage, CCS infrastructure) and piloting and upscaling to commercial scale of the actual production units will all influence the speed of change.

Keywords: Supply chain; Construction; Buildings; Transport infrastructure; Embodied carbon; Decarbonization; Carbon abatement; Carbon mitigation; Emissions reduction; Low carbon technology; Scenario analysis

Acknowledgements

First and foremost, I would like to thank my supervisors, Filip Johnsson and Johan Rootzén, for making it possible for me to finalize this thesis in the limited time available under the circumstances. Without your support and guidance, there is no way I would have managed it. I am also very grateful for all the opportunities you have given me during my time at Chalmers to reach out with my research in all kinds of internal and external forums. Moreover, I greatly appreciate our collaboration and valuable discussions and the freedom and flexibility with which you have allowed me to design and conduct the research. At the same time, you have both provided helpful advice and backing whenever I have asked for it or when I have put too many irons in the fire.

I thank my great colleagues at the Energy Technology division for the warm and inspiring work environment. I have missed you greatly over this strange last year of working from home and am very much looking forward to things hopefully being back to normal after I am back from parental leave.

I would also like to thank my dear family and friends around the world. A special thanks to my dearest friends, Linda and Sophie, for never giving up on me, even in periods of absence. I am so fortunate and happy for the sisterhood I feel with you two.

To my parents, I have the deepest gratitude for you always being there for me, through thick and thin. It means the world to know that when things are tough, your door is always open for me to take some time out and recharge.

To Stefan, I feel so blessed to have met you. Thank you for your calm and patience with me. I am so excited about the incredible journey we have embarked upon.

Last but definitely not least, thank you Noah for being my eternal sunshine. Whenever I need new inspiration, all I have to do is take a break, spend some time with you and I realize why I put in the hard yards. It is for your future and the future of your new siblings. For you, I promise to keep putting my heart and soul into doing whatever I can to create a cleaner, brighter, low-carbon world.

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their Roman numerals:

I. Karlsson, I., Rootzén, J., and Johnsson, F., "Reaching net-zero carbon emissions in construction supply chains – Analysis of a Swedish road construction project," *Renew. Sustain. Energy Rev.*, vol. 120, 2020, https://doi.org/10.1016/j.rser.2019.109651.

II. Karlsson, I., Rootzén, J., and Johnsson, F., "Achieving net-zero carbon emissions in construction supply chains – multi-dimensional analysis of residential building systems", To be submitted, 2020

III. Karlsson, I., Rootzén, J., Toktarova, A., Odenberger, M., Johnsson, F., and Göransson, L., "Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement," *Energies*, Aug. 2020, https://doi.org/10.3390/en13164136.

Ida Karlsson is the principal author of **Papers I–III** and conducted the literature reviews, the modeling and calculations for these papers. Professor Filip Johnsson, who is the main academic supervisor, together with co-supervisor Johan Rootzén, contributed with discussions and the editing of all three papers. Alla Toktarova, Mikael Odenberger and Lisa Göransson contributed with reviewing and discussions as part of the refining of **Paper III**.

Related publications not included in this thesis

IV. Karlsson, I., Toktarova, A., Rootzén, J., and Odenberger, M., "Mistra Carbon Exit Technical Roadmap - Buildings and Transport Infrastructure," 2020. [Online]. Available: https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-buildings-and-transport-infrastructure.

V. Karlsson, I., Toktarova, A., Rootzén, J., and Odenberger, M., "Mistra Carbon Exit Technical Roadmap - Cement Industry," 2020. [Online]. Available: https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-cement-industry.

VI. Toktarova, A., Karlsson, I., Rootzén, J., and Odenberger, M., "Mistra Carbon Exit Technical Roadmap - Steel Industry," 2020. [Online]. Available: https://www.mistracarbonexit.com/news/2020/5/19/technical-roadmap-steel-industry.

VII. Johnsson, F., Karlsson, I., Rootzén, J., Ahlbäck, A., and Gustavsson, M., "The framing of a sustainable development goals assessment in decarbonizing the construction industry – Avoiding 'Greenwashing,'" *Renew. Sustain. Energy Rev.*, vol. 131, no. July, 2020, doi: 10.1016/j.rser.2020.110029.

VIII. Toktarova, A., Karlsson, I., Rootzén, J., Göransson, L., Odenberger, M., & Johnsson, F. (2020). "Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study". Energies, 13(15), 3840. https://doi.org/10.3390/en13153840

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1 Introduction

1.1 Background

Anthropogenic greenhouse gas (GHG) emissions are a serious concern for human civilization, with recent climatic changes already having widespread impacts on human and natural systems [1]. The central aim of the multinational climate agreement made in Paris in 2015 is to restrict the global temperature rise to well below 2°C above pre-industrial levels, while pursuing efforts to limit the temperature increase to 1.5°C [2]. Indeed, the landmark 2018 special report from the UN Intergovernmental Panel on Climate Change [3] presented a stark picture of the dramatically different world we will inhabit if global average temperatures rise by 2°C, as compared to a 1.5°C scenario. Limiting global warming to well below 2°C will require drastic reductions in the global levels of GHG emissions, so as to achieve net-zero carbon emissions by Year 2050 and negative emissions thereafter [4]. In response, more and more countries are setting goals for net-zero emissions, as is the European Union (EU) [5]. Sweden has set more ambitious climate targets than the EU, with a long-term goal to have net-zero emissions[1] in Year 2045, and thereafter net negative emissions [6].

Consequently, the climate emergency calls for immediate and urgent action to start the transformation towards deep GHG emission cuts in the coming decades, and the UN Environment Program has stated in a recent report that it will be necessary to cut almost 8% of GHG emissions each year from Year 2020 [7]. The built environment sector has a vital role to play in responding to the climate emergency, with the construction, maintenance and operations of built structures responsible for around 40% of global GHG emissions [8], with the construction responsible for close to 25% of global carbon emissions [9].

To date, GHG emissions released during the operational life of buildings have been in focus, particularly regarding policy initiatives to improve building-related GHG emissions [10], [11]. However, the share of operational emissions has been reduced in recent decades owing to the implementation of more-energy-efficient building technologies, together with the increasing use of low-carbon energy carriers in the operation of buildings [12]–[18]. Consequently, the role of embodied GHG emissions, i.e., emissions that occur during the manufacturing, transportation, construction and end-of-life phases of built assets, has taken on greater importance.

At the same time, the UN Environment Program Global Status Report 2019 for the building and construction sector reported that in 2018 GHG emissions associated with construction and operation of buildings had increased by 2% since 2017 and by 7% since 2010, driven by increases in floor area and population expansions [19]. Similarly, in Sweden, the GHG emissions from the building sector have increased by 4% over the last 3 years, driven by increased levels of imported building products [20]. Indeed, embodied GHG emissions will continue to rise under a business-as-usual scenario given that the global building stock is set to double by Year 2050 [8], [21], while more than half of the urban infrastructure that will exist in 2050 is yet to be built [22], [23]. In the national perspective, Sweden needs 600,000 new homes up to Year 2025 [24], as well as substantial investments in renewed infrastructure to create an efficient and low-carbon transport system [25], [26]. Furthermore, as embodied GHG emissions are occurring upfront, they are especially relevant considering the need to decarbonize the global economy while respecting budgetary limitations regarding GHG emissions [10].

Therefore, it is essential to map out in the lead up to mid-century how mitigation measures can be allocated, identifying those measures that can be applied already at present and those that will require longer lead times to be implemented [27]. This is necessary to ensure that both low-hanging-fruit (incremental) measures are implemented, while starting the necessary planning for the more transformative measures that will be required to reach zero or near-zero emissions by mid-century [28]. The emphasis in the work of this thesis is thus on the challenges associated with achieving net-zero carbon emissions from construction and the construction supply chains within the next two to three decades.

In view of the stringent, long-term climate objective and the project-based, risk-averse construction industry, which tends towards slow uptake of innovations [29], [30], the main value of this work is to add a supply chain and time dimension that allows one to envisage where and when the different mitigation measures can and must be in place, if emission reduction targets are to be met. By including these dimensions, we identify where in the supply chain large shifts are needed, highlighting strategic choices needed already now to make the necessary provisions allowing for net-zero emissions to be reached in 2045.

Thus, we link this work to the net-zero reduction target set by the Government of Sweden, as well as the targets set by the Swedish Construction and Civil Engineering sector, implying a reduction of 50% up to Year 2030 (as compared to Year 2015), in addition to a net-zero target up to Year 2045 [31].

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[1] Defined as at least 85% domestic reductions with the remainder achieved through so-called supplementary measures, e.g., reduction overseas or capture and storage of carbon dioxide from biogenic sources.

The work of this thesis has been carried out within the Mistra Carbon Exit research program, which is aimed at identifying and analyzing the technical, economic and political opportunities and challenges for Sweden to reach the target of net-zero GHG emissions by Year 2045 within the supply chains of buildings, transportation infrastructure and transportation [32].

1.2 Aim and scope

The overall objective of the thesis is to explore the challenges associated with reducing CO_2 emissions from the buildings and transport infrastructure construction supply chains. The ambition is to analyze the current and future potentials for GHG emissions reductions by considering the development, over time, of emission abatement measures in different parts of the construction supply chain. The three appended papers assess these potentials across the construction supply chain, while conducting detailed analyses of the primary production processes for steel and cement. The work starts with the development of a comprehensive inventory of abatement options in the supply chains of buildings and transport infrastructure construction, including technologies and practices that are available currently and that are expected to be available on a timescale leading up to Year 2045. The main goal is to analyze the extent to which abatement technologies across the construction supply chain can reduce GHG emissions if combined to extract maximum potential, while identifying the key barriers towards their implementation.

Paper I takes a road construction project as a case study, mapping the materials and emissions flows and providing a description and assessment of the options for reducing CO_2 emissions at the present moment and over time, while comparing the results to the abatement measures and CO_2 emissions reductions achieved in the actual project. The abatement measures are combined in scenarios that cover specific conditions, with the focus on parameters that influence strategic considerations, including access to biofuels and enactment of transformative measures, such as electrification and carbon capture.

Paper II provides a multidimensional assessment of the potential for GHG emissions abatement in relation to the construction of multi-family housing units, with the assessment conducted along the value chain from material production via material transport and construction up to the point of a finished building. The first dimension relates to different building designs with the same functionality. The second dimension relates to time, ranging from currently available technologies and practices to those that are expected to become available up to 2045. The third dimension analyzes the abatement potential at different points in the supply chain, from primary material production via material processing and composition to the design of the final building structure.

Paper III adopts a national perspective, using analysis of the material, energy and emissions flows in combination with an extensive literature review to assess the current status of emissions from the Swedish construction sector. Thereafter, it analyzes the extent to which abatement technologies across the construction supply chain can reduce GHG emissions if combined to maximize their potentials based on implementation timelines linked to their technical maturity and expected extent of implementation. A roadmap is created that explores how the flows change depending on different technical and strategic choices regarding the abatement focus, including bio-based measures, carbon capture, electrification and material efficiency. By matching the short-term and long-term goals with specific technology solutions, the roadmap makes it possible to identify key decision points and potential synergies, competing goals, and lock-in effects.

1.3 Outline of the thesis

The thesis consists of an introductory section and the three above-mentioned appended papers. Section 1 gives the background of the work and places the appended papers in a broader context. Section 0 outlines the research methodology applied in the appended papers. Section 3 details the main components of embodied GHG emissions associated with the construction of buildings and transport infrastructure, while Section 4 presents the detailed inventory of abatement options with potentials and implementation timelines, which is used as the key input to the appended papers. Section 5 summarizes and discusses some of the key findings of the thesis work. Finally, in Section 6, ideas for future work are presented.

2 Materials and Methods

The work presented in this thesis has been structured as a participatory integrated assessment, i.e., a systematic approach to developing theoretically coherent and practicable decarbonization strategies, while involving key stakeholders in the process [33], [34]. Quantitative analysis methods, including scenarios and stylized models, are combined with participatory sessions that involve relevant stakeholders in the assessment process. The quantitative analysis uses spread-sheet based models tracking material flow, energy use and GHG emission in an individual project or in the sector/supply chain, where the participatory process serves to identify the main abatement options, as well as to adjust decisions and assumptions regarding abatement portfolios and timelines, so as to make these as realistic and feasible as possible. . The stakeholders, which included industry representatives and experts along the supply chain, material suppliers, contractors, consultants, clients and governmental agencies, provided input and feedback throughout the study development periods.

A life cycle assessment (LCA), a methodology for detailing resource flows and associated environmental impacts, is often used to appraise the climate impact of a product or service, such as a building [35], [36]. Numerous LCA studies have been performed which detail the carbon footprint of buildings (see reviews in e.g. [11], [37]–[43]) or transport infrastructure (see e.g. [44]–[49]). There is also evidence in literature of LCA studies which investigate strategies to reduce the embodied carbon of the constructions or elements there of (for buildings see reviews in e.g. [13], [14], [17], [50] and for transport infrastructure see e.g. [51]–[56]). However, whereas existing literature is of benefit to decision making for projects taking place in the near term, these are insufficient basis for longer term policy making, which will require comprehensive assessments into not just current but also prospective future abatement options and potentials. To lay foundations for the low-carbon transition in building construction supply chains, there is a need to complement traditional life cycle assessment approaches with dimensions and dynamics in the context of variations in the surrounding industrial and environmental system [57]–[60].

The work included in this thesis thus reviews and expands on existing literature, using a foundation of lifecycle assessment data, while moving beyond static analyses of embedded carbon by considering the development, over time, of emission abatement measures in different parts of the construction supply chain. The work consequently has a supply chain focus and a systems perspective. The supply chain approach involves analyses of opportunities and barriers for mitigating carbon emissions along the industry supply chains, from the input of raw materials, over refining via primary and secondary activities, to the final products and services demanded by the end-users [61], [62].

This approach is deemed appropriate as the construction sector has a highly complex and multi-tiered supply base, whereby companies operate in a fragmented supply network that creates major challenges in adopting a whole-life approach to construction, as well as in creating shared goals [63]. Supply chain integration with inclusion of upstream parts of a building supply chain (i.e. sub-contractors, suppliers and manufacturers) has been found to be integral for the delivery of sustainable buildings [64], and the supply chain approach further provides the ability to apply a broader viewing lens to both opportunities and barriers, as these often emerge in the links between economic sectors and individual actors [57].

The focus of the work is predominantly on GHG emissions from materials production, mass and material transport, and the construction process up to the point of a finished construction, [11] (i.e., corresponding to lifecycle stages A1–A5 in the European lifecycle assessment standard, EN 15978:2011 [8]). The workflow of this thesis is depicted in Figure 1.

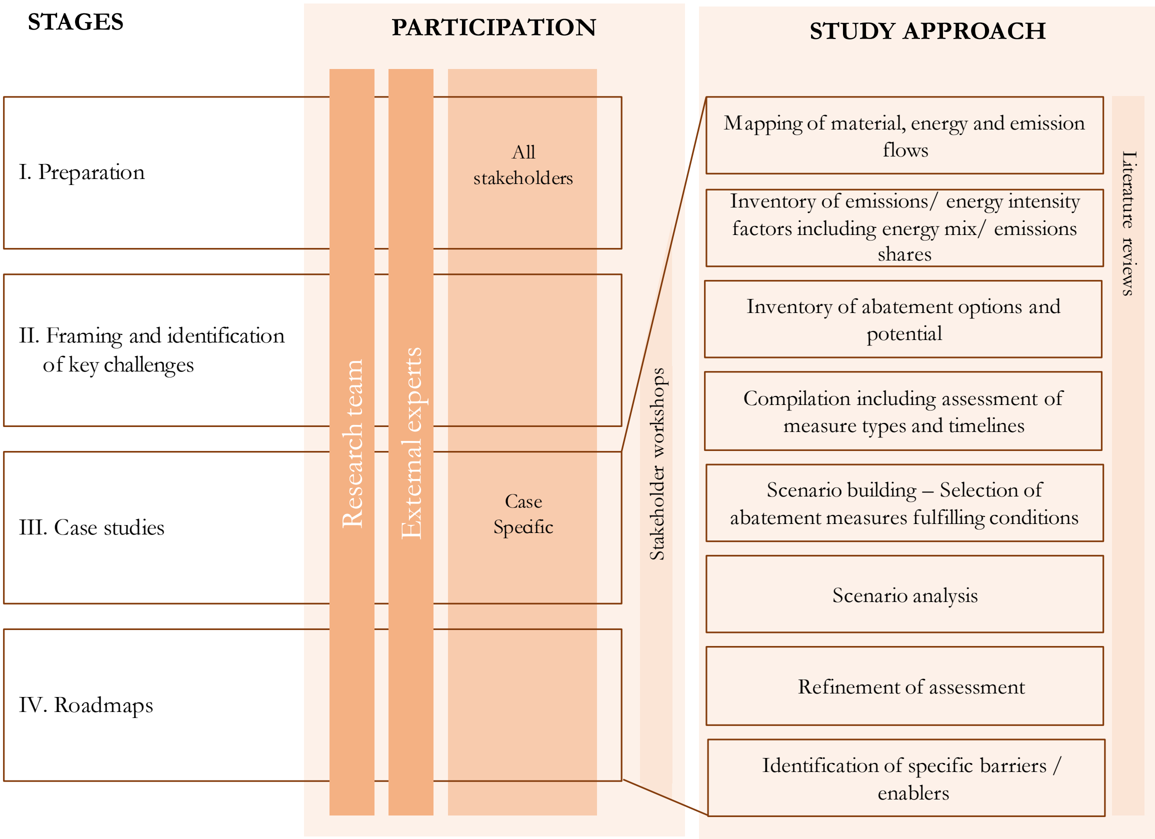

Figure 1. Outline of the methodological approach (adapted from Karlsson et al [65])

In the preparation stage (Stage I), the research team defined the initial scope of the assessment and engaged stakeholders in the assessment. Framing with stakeholders (Stage II) implied a high-level classification of the challenges and potential solutions associated with the low-carbon transition in the construction sector, together with identification of suitable benchmark cases. The outcomes from the two first stages are detailed in a conference paper presented by Rootzén and Johnsson in 2018 [66].

The case studies include the analysis of a road construction project and the study of representative building systems for multi-family buildings, as reported in **Papers I** and **II**, respectively. These apply the same basic methodological approach, whereby analyses of material and emissions flows are combined with the identification of possible GHG abatement options relevant to the respective construction supply chains. The latter are based on inputs obtained from supply chain stakeholders and comprehensive literature reviews, including the estimated abatement potential and expected timelines for implementation. The outcomes from the case studies are used as inputs to the development of decarbonization roadmaps (Stage IV), which are developed for the Swedish cement and steel industries, in addition to the roadmap for the supply chains of buildings and infrastructure, which is reported in **Paper III**. In addition to the detailed material, energy and emissions flows included in **Paper III**, the associated technical reports [67]–[69] contain more detailed assessments of pathway choices, along with the barriers, risks and enablers [70], [71].

Material flow analysis (MFA) is a tool for the measurement and prediction of environmental pressures arising from the use of materials in an economy. It provides a system-wide perspective and has emerged as the primary methodological framework among flow accounting approaches, as it offers the greatest scope of applications for environmental accounting and systems analysis [72]. **Papers I** and **II** are based on previously established material accounts for the specific case study objects. **Paper III** establishes an estimate of the material and energy use in, and associated GHG emissions from, the Swedish building and construction industry. It compares existing estimates with mapping of the material, energy and emissions flows through the supply chain of buildings and transport infrastructure construction, produced via a literature review of lifecycle analyses and equivalent studies[2]. The estimate is validated by comparing the resulting emissions for specific materials with available data.

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[2] Literature searches were conducted in Scopus and Web of Science with search string algorithms that targeted a combination of LCA OR "life cycle analysis" OR "life cycle assessment" OR "carbon footprint" AND building* OR construction OR infrastructure with subsequent screening to identify studies of relevance within the scope of this study, e.g., transport infrastructure and buildings of equivalent design and construction techniques to those in Sweden.

Papers I and **II** review emissions intensity factors based on LCA data, along with other literature on key materials, activities and fuels associated with the construction of road infrastructure and buildings, respectively. When deemed feasible, the emissions intensity factors were divided into components, to enable assessments of different mitigation measures. While **Papers I** and **II** focus on the GHG emissions flow, **Paper III** also provides an analysis of the energy flows of the Swedish building and construction industry over time. Thus, **Paper III** establishes energy intensity factors along with the energy mixes in the production of reference materials and energy carriers. In the pathway analysis described in **Paper III**, the energy intensity factors, and energy mixes, are adjusted based on the abatement options selected and applied in the assessment for each supply chain activity. The compilation of material, energy and emissions flows serves as the baseline when applying abatement potentials identified in the abatement options review.

The inventory of GHG abatement options is established by means of a comprehensive literature review[3], which includes industry and governmental agency reports (gray literature), as well as product searches using certified program operators. The main types of abatement options considered in the assessment are material efficiency and optimization measures, together with shifts in material production processes, transport vehicles and construction equipment technologies, and fuel substitutions in both equipment and production plants. The options include certain reuse and recycling measures that result in emissions reductions, albeit not for the specific purpose of resource conservation. The inventory comprises current best-available technologies, practices and products, as well as emerging technologies that are deemed likely to become available in the period up to Year 2045, with implementation timelines linked to their levels of technical maturity.

A timeline is applied to test the potential implications for climate impact when constructing the same assets while applying a combination of GHG abatement measures along the supply chain that are appraised to have reached commercial maturity at different points in time.

From the abatement inventory, portfolios of abatement measures for the respective supply chain activities are constructed with selections of measures applied to a timeline. Scenario building and analysis are used to highlight key strategic aspects regarding the choice of mitigation focus. This is regarded as a useful methodological tool to address the uncertainty, allowing for the identification of key points at which it is most effective to act, as well as to determine the expected range of emissions reduction associated with any given management option [73]. The abatement measures are, thus, combined into scenarios according to specific conditions. In **Paper I**, these conditions focus on parameters that may influence strategic considerations, such as access to biofuels and the enactment of transformative measures. In **Paper II**, the conditions focus on measures implemented along the supply chain, from primary material production, via material processing and composition to the final building design and structure, including the impacts on material transport and the construction process. Finally, **Paper III** creates conditions based on the abatement focus, including bio-based measures, carbon capture, electrification, and material efficiency. Taken together, **Papers I–III** provide a comprehensive assessment of the roles of technologies and measures that are commercially available today and of emerging technologies that are still under development.

A simplified schematic of the calculations and compositions of the abatement measure portfolios is presented in Figure 2. The waste material parameter is analyzed separately in the building system study in **Paper II** but is included in the material parameter in **Papers I** and **III**. Regarding the supply chain levels of analysis, the road construction case study in **Paper I** involves abatement measures in primary material production, while the building study and roadmap analyses in **Papers II** and **III** include all three levels of analysis, from primary material production, via material composition, to material efficiency measures at the structure level.

[3] Literature searches were conducted using a combination of academic bibliometric databases (Scopus and Web of Science) and web browser searches were used to enable sourcing of the relevant gray literature, which is not so evident in academic bibliometric databases. This was followed by a snowballing approach to identify relevant references in articles already included in the review. Search string algorithms targeted a combination of the material/activity in question (focusing on the key emissions sources) together with "carbon emissions" OR CO_2 OR GHG OR "greenhouse gas emissions" AND abatement OR "emission* reduction" OR mitigation OR decarbonization. Searches of best-available products, focusing on products available in the Nordic market, were also conducted via program operators for independently verified and registered environmental production declarations, such as The Norwegian EPD Foundation, The International EPD® System and Institut Bauen und Umwelt e. V.

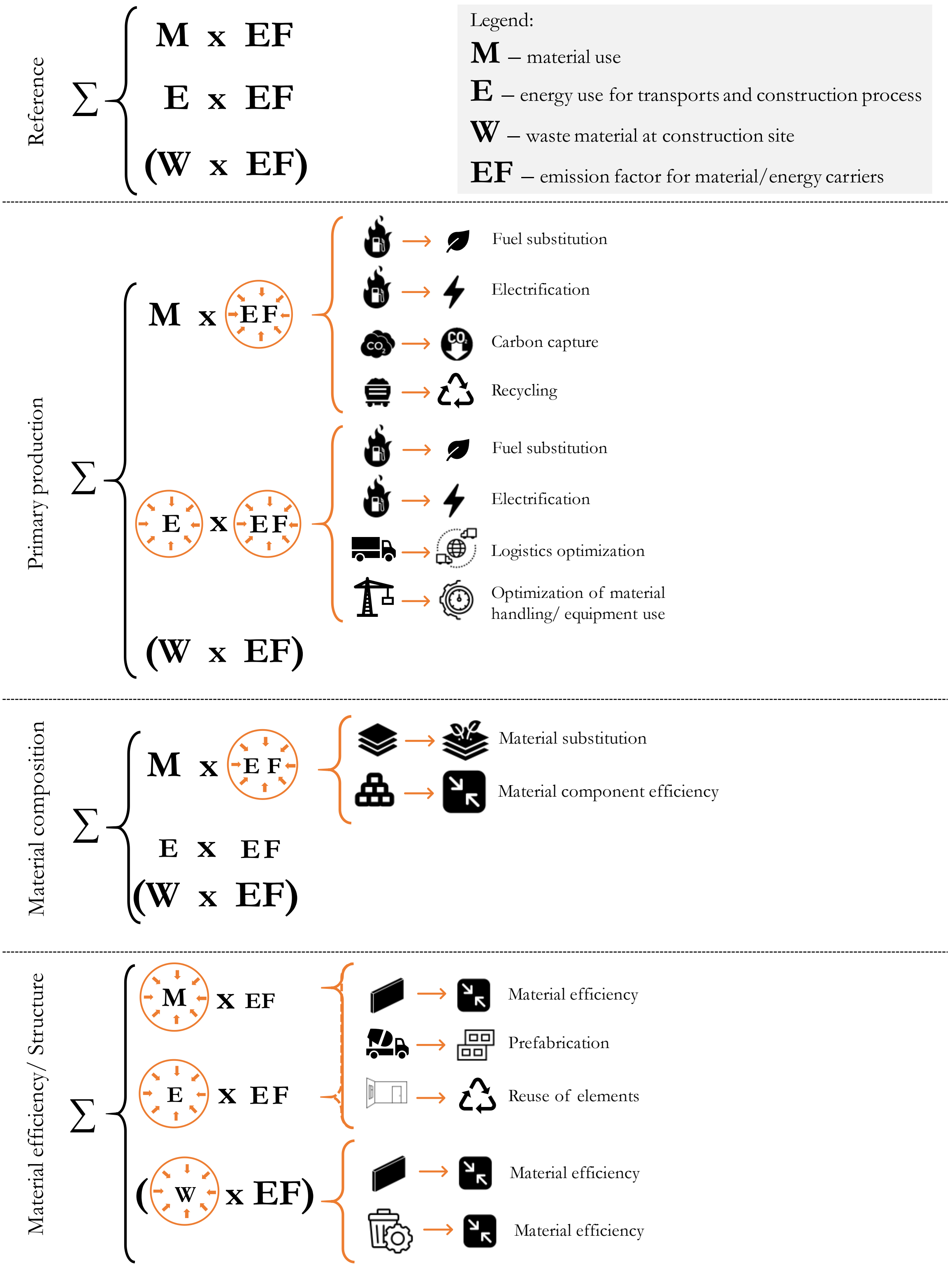

Figure 2. Simplified schematic of the calculations of embodied GHG emissions associated with the constructed assets, and the impacts on the calculation parameters from the compositions of the different abatement measure portfolios along the supply chain. The parameters include material use in units of material for all the materials included in each specific study (M), energy use for transport and the construction process per energy carrier (E), material waste at the construction site (W), and the emission factor per unit for each material and energy carrier included in the analysis (EF). The size of the parameter letters indicates the relative size of the embodied carbon emissions, where the reference level represents business as usual construction based on LCA and data from literature and data bases. The orange circles denote parameters impacted by the abatement measures applied in the specific abatement measure portfolio. The portfolios are additive, where the abatement measures detailed in the lower portfolios build on the abatement measures included in previous portfolios.

In all three papers, the scenarios are primarily geared towards reaching the medium-high range of the emissions reduction potentials for each selected abatement measure (as detailed in Section 4). The measures and timelines that are largely compatible with the roadmaps and pathways developed within the European Commission long-term climate strategy (combination of electrification and hydrogen scenarios) [74], the Mission Possible project of the Energy Transition Commission [75], and the industry roadmaps developed within the Fossil Free Sweden initiative on fossil-free competitiveness [76]. The scenario analyses assume that emission factors for electricity will decrease in accordance with the scenario analysis provided by the Swedish Energy Agency [77] and estimates made by the European Energy Agency, implying that GHG emissions related to electricity generation will reach zero in Year 2050 [78].

While the work is performed in a Swedish setting, the analyses of abatement options, timelines and pathways should be generally relevant and applicable, at least on the European level [8], [79]. Likewise, although some of the conclusions are valid only under specific conditions, it is clear that many of the challenges that are raised in this thesis work, which must be overcome to achieve a transition to zero-CO_2 production, and the practices applied in the supply chains for buildings and infrastructure, are universal [10], [21], [23].

3 Embodied GHG emissions associated with the construction of buildings and transport infrastructure

The total climate impact of construction processes in Sweden is estimated to be around 10 $MtCO_2e$ per year, which is equivalent to 20% of annual GHG emissions in Sweden, of which building construction account for roughly 75%, and civil engineering and public works for around 25% [80]–[82]. Most of the GHG emissions associated with construction supply chains are in the form of CO_2 emissions, while the LCA data used as a foundation to estimate the climate impact of products and processes also include other GHG emissions such as fugitive methane emissions associated with fossil fuel production [83], [84]. The work of this thesis includes the climate impacts linked to the construction of buildings and transport infrastructure. Thus, it does not include the construction of, for example, utilities such as waterworks, wastewater treatment plants, power plants and power lines. The construction of buildings and transport infrastructure represents the majority of construction activities in Sweden, equivalent to around 80% of investments [85]. Consequently, this work revolves around embodied emissions, which in addition to the GHG emissions associated with the production and transport of materials used and energy consumed at the time of erection/construction, also includes emissions associated with renovation of the constructed assets [43]. However, the production stage generally dominates the whole-life embodied emissions, as compared to the replacement and refurbishment of both buildings [11], [41], [86] and transport infrastructure [48], [49], [55].

As regards the source of the embodied GHG emissions, a global review and supply chain analysis conducted by Onat and Kukucvar [87], based on an input-output analysis, has shown that currently the main emissions of the construction industry are found in the supply chain, i.e., in material production, ranging from 58% to 83% for the different countries included in the analysis. LCAs also indicate that the majority of embodied emissions originate from materials rather than the transport and construction phases (for reviews, see [11], [40], [88]–[90]). Indeed, the construction sector is a large consumer of raw materials, with Kumari et al. [50] reporting that globally, 60% of raw materials are being used for civil works and building construction.

It is worth noting, however, that most LCA studies do not include emissions associated with the groundwork or soil stabilization needed to prepare the construction site. Depending on the conditions at the construction site, the groundwork can contribute to a substantial share of the embodied GHG emissions of new buildings [81], [91].

Regarding materials, the materials used for the structures of buildings generally represent more than half of the embodied emissions associated with buildings [13], [92], [93]. A review by Habert et al. [94] demonstrated that cement accounted for 36% of the CO_2 released globally by construction activities in 2010, while steel accounted for 25%, plastics 8%, aluminum <4%, and brick <1%. Other significant contributors to emissions, particularly for low-energy housing and wooden-frame structures, include insulation materials and gypsum plasterboard [88], [95].

These data correspond well to the results of the detailed analysis of the components of current GHG emissions associated with the construction of buildings and transport infrastructure performed in **Paper III**, the results of which are exhibited in Figure 3. We see here that cement and steel together with diesel use in construction processes and material transport account for the majority of the GHG emissions associated with building and infrastructure construction.

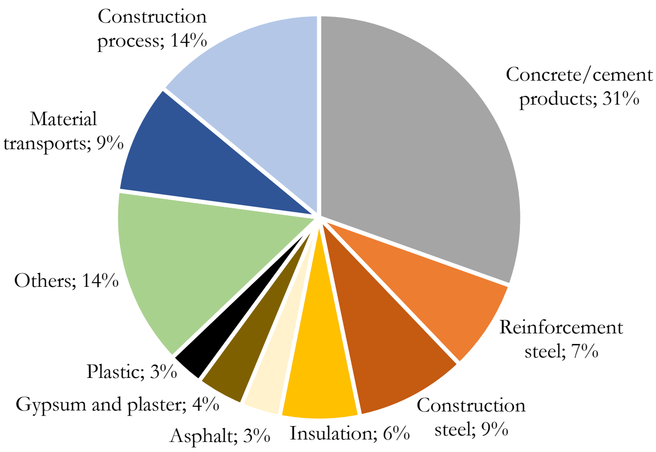

Figure 3. Components of the annual embodied GHG emissions associated with the construction of buildings and transport infrastructure in Sweden. The "Others" category includes materials such as aluminum and glass and wood products (adapted from Karlsson et al [82]).

4 Detailed inventory of GHG emissions abatement options and potentials

This section details the developed inventory of GHG emission abatement options and potentials, on an overall level as well as per material and activity, as this inventory provides the basis for the analyses performed in the three appended papers. The inventory is aimed at being a comprehensive but not exhaustive review, and includes the segments listed in Table 1.

Table 1. Lists of segments included in the inventory of GHG emissions abatement options and potential (with links to the respective segments).

General abatement measures	Material/activity-based abatement measures

• General abatement measures
• Material efficiency measures
   o Prefabrication
   o Hybrid solutions
   o Recycling and other circularity measures
• Bio-based measures – fuel and material substitution
• Electrification
• Carbon capture
	• Concrete and other cement-based products
	• Steel production and use
	• Aluminum
	• Insulation
	• Plastics
	• Gypsum and plaster
	• Timber and other forest-based products
	• Engineered wood products
	• Windows/glass
	• Asphalt production and paving
	• Heavy transport systems
	•
	• Construction process

4.1 General abatement measures

The best way to reduce embodied carbon is through prevention. This involves considering alternative strategies for delivering the desired function, such as increasing the utilization of existing assets through renovation [8], [96]. By avoiding new construction, potential embodied GHG emissions are eliminated, which is why the first step would include efforts early on, in all the planning processes and among all the actors, to avoid new construction all together where possible, and if this is not possible, to seek to reuse old assets.

If new construction or renovation is deemed necessary, the key GHG emissions mitigation options currently available for materials used in construction include: material efficiency; circularity measures; and material substitution toward materials/components with lower levels of embodied carbon (for reviews, see [11], [13], [50], [92], [97]–[99]). Other abatement measures include fuel changes and energy efficiency measures in material production facilities [100]–[104].

Material efficiency measures also reduce transport needs and, thereby, emissions associated with transport systems. Other current abatement measures for material transports include optimization of logistics and transport distances, fuel substitution or changing mode of transport [75], [105], [106].

For construction processes, the main current abatement measures are increased levels of prefabrication in combination with enhancing the efficiency of the construction by optimizing material handling requirements, site layout, utilization of vehicles, and choice of construction equipment for the intended use [13], [50], [107], [108]. Fuel substitution and hybridization are important technical abatement measures for the various items of construction machinery [107], [109], [110].

In the longer term, transformative measures will be required, including direct or indirect electrification (hydrogen/power to X) and/or the application of carbon capture in material production facilities [101], [103], [104], [111], [112], combined with electrification or use of fuel cells in heavy trucks and construction equipment [75], [111].

4.1.1 Material efficiency measures

Material efficiency is a key abatement measure for all construction materials, and it deserves greater attention in policy and climate mitigation discussions. Current design practice is to optimize based largely, if not exclusively, on the cost and time of construction [113]. Evidence (see [75], [98], [101], [114]–[118]) suggests that, on average, one-third of overall material use could be saved if designs were optimized for material use rather than for cost reduction, since downstream production (and design) are generally dominated by labor costs rather than material costs. Around 20%–30% of total production costs are material costs, of which structural materials make up about half, and of that individual materials represent only a small share [119], [120].

Therefore, there is no strong economic incentive for industry to reduce the amount of materials used. Thus, excessive use of materials can often be attributed to a standardized design process in combination with minimal economic gain from an optimized design.

The design process for residential buildings is often initiated by preliminary blueprints from an architect, with the thicknesses of structural parts being estimated based on previous projects and handbooks [121]. For example, it is easier to use constant cross-sections across a structure than to design each beam and column individually, since this facilitates faster construction in addition to it being less costly from the designers perspective to stick to established practices and designs [113], [114]. The potential for optimization during the later stages of the design is often neglected due to the minimal economic gain [121]. In summary, motivations to use excessive amounts of materials are driven by asymmetric costs of product failure relative to the costs of over-specification, resulting from over-specified components being copied across projects to minimize costly design time and cheaper manufacture of standard parts [99].

As a consequence, material efficiency includes measures such as reducing construction waste, optimizing the building form and design of layout plans, avoiding overdesign, and the use of light-weight constructions [13], [14], [17]. While these measures often face coordination costs today, such costs could fall significantly in the future in a more digitized construction industry that also employs more advanced techniques, including 3D printing [101].

To realize the potentials of these material efficiency measures, close collaboration between all the relevant actors in the supply chain will need to be initiated already during the design and early procurement phases [29], as the decisions taken in the conceptual design phase have the greatest impact on the total building performance [122], [123]. Early engagement in the design process will allow for a thorough investigation of the barriers, enablers and drivers linked to these measures, while close communication throughout planning and construction ensures enactment of the material efficiency measures during the actual construction [113].

4.1.1.1 Prefabrication

One method that has gained popularity for reducing construction waste, and thereby CO_2 emissions associated with material production, is the use of off-site construction, which involves the offsite manufacturing and preassembly of building components prior to installation at the construction site [124]. Indeed, the generation and transport of waste material can contribute a significant share of the embodied CO_2 emissions [11], [125]. Offsite manufacturing in the construction industry ranges from simple precast beams and columns to prefabricated walls and full modular houses [126]. Compared with onsite construction, factory production of construction components can have much lower resource inputs and reduced waste outputs [90], [127]. Prefabricated elements can increase flexibility and the possibility to reuse concrete and enable the more-efficient usage of machines and labor on a construction site [119].

An increased level of prefabrication also means shorter construction times, which means, on the one hand, less disruption for nearby residents and the local environment [90], [128]. On the other hand, the transport of concrete elements is difficult to make as efficient as the transport of in situ cast concrete, i.e., the concrete that is mixed in the factory and delivered to the construction site in liquid form. While estimates vary, studies have shown that prefabrication can reduce embodied carbon emissions in buildings by up to 15%, as compared with cast-in-situ methods [129], [130].

4.1.1.2 Hybrid solutions

To date, material industries have tended to work in isolation when developing products for the construction market, as well as structural systems. However, combinations of materials can be highly beneficial, in terms of resource efficiency, architectural solutions, and considerations related to structural optimization [131]. Hybrid constructions, hybrid elements, and hybrid components are all terms that are applied to solutions where wood is combined with other materials to achieve the desired properties. By collaborating and matching materials with specified needs through analyses of potential products with increased efficiency and functionality, the consumption patterns on the market could be transformed in a more sustainable direction, according to the “right material in the right place” dogma [31]. Internationally, hybrid-based construction has not yet been implemented on a broad front, although interest is growing both in industry and in research to understand its possibilities[128], [131].

4.1.1.3 Recycling and other circularity measures

Circularity measures can be implemented in various stages of the construction supply chain: from increased recycled content used as raw material in primary material production, via recycling of materials in material processing, to the reuse of structural elements or modules [13]. For many materials, such as virgin (primary) steel or aluminum, the levels of embodied GHG emissions are much higher than for recycled materials because more processing and, consequently, significantly more energy is used in the extraction process from ore than in the production process from recycled raw material [11], [132].

Indeed, reducing virgin material use through the recycling and reuse of materials and structures has been shown to be an effective approach to reducing embodied GHG emissions (see [13], [132]–[134]).

Increased reuse would require construction materials and components from previously demolished sites to be properly maintained and stored, so as to enable their further use in new projects. Through maintaining existing building elements, reductions of the quantities of material used and construction waste could be achieved [135].

Service life extension, when coupled with the use of more durable components, such as design for flexibility, adaptability and reuse, may also reduce embodied GHG emissions over the lifecycle of a structure, although there are only limited studies examining the impacts of such strategies [11].

Moving towards the implementation of circularity principles in the building and construction sectors requires a new process design strategy in which various disciplines in the supply chain are integrated upfront, as observed by Leising et al [136]. In addition to requirements for new business models and policy interventions, there are needs for supply chain integration and risk management frameworks to enable supply chain organizations to re-evaluate their processes with the goal of accelerated transition to circularity practices [126].

4.1.2 Bio-based measures – fuel and material substitution

Changing to bio-based construction materials has been demonstrated in various case studies in the literature to reduce embodied GHG emissions (see, for example, [13], [99], [137]), particularly if the substitutes require less industrial processing [11], [92]. While substitution of timber in large building components has a relatively high reduction potential, there are large variations in the potential depending on the building design [138]. Biomass substitution also has potential within advanced bio-based products, such as resins, plastics and bitumen [139].

Further, biomass is a major driver of decarbonization with respect to the reduction of fuel carbon intensity, whether it is fuels used in industrial material production or transport fuels, with the main differences between applications being related to varying feedstocks and conversion technologies [140]. Bioenergy is, however, linked to serious sustainability concerns, and its overall potential is constrained by the competition for food production and other land uses [141], [142]. For forestry-derived biomass, the associated GHG emissions partly depend on the forest management regime, although there is also debate as to the climate benefits that can be derived from using biomass to substitute fossil fuels and feedstocks, as compared to maximizing forest growth for carbon uptake (*cf.* Berndes et al. [51] and references therein). In general, the currently common practice in LCAs to assume that biogenic CO_2 emissions are climate-change-neutral tends to underestimate the benefit that can be accrued from storing carbon in long-lived products, whereas it overestimates the benefit that can be derived from short-lived products, such as biofuels incinerated shortly after harvest [143]–[146]. When being used in long-lived products such as built assets, wood products can retain the carbon and may thus be considered a temporary carbon sink, provided a stable carbon pool in the forests from where the products are harvested [146]. However, the result can be substantially different if the carbon sequestration at the forest is assumed to occur before or after material manufacturing [147], why the temporary carbon sequestration has not been included in this thesis work.

Thus, the use of biofuels as a GHG emissions abatement measure (for example, high-temperature processes in industry and advanced biofuels for road freight) is predominantly seen as being relevant to facilitating reductions in the use of fossil fuels during a transition period until electrification reaches its full potential [75]. In the longer term, land constraints imply that biofuels should primarily be deployed only in applications where the substitution of carbon-based fuels is particularly difficult, such as in aviation and long-distance ship transport [74], [148].

Biomass may also be increasingly used in the application of bioenergy with carbon capture and storage (BECCS), so as to promote negative emissions (i.e., CO_2 removal) [141], [149]. The extent to which biomass will supply liquid fuels in a future net-zero emissions energy system thus depends on advances in conversion technologies, competing demands for bioenergy and land, the feasibility of other sources of carbon-neutral fuels, and integration of biomass production with other objectives [111].

4.1.3 Electrification

Given the technical advancements and the rapid decarbonization of the power supply, replacing fossil fuels with low-carbon electricity has become a centerpiece of the GHG emissions abatement strategy for the heat supply in many industrial sectors [150], [151].

Electrically powered technologies can cover the entire temperature spectrum relevant to industrial thermal processes, with a range of technologies being available for high-temperature purposes, such as induction, resistance, plasma heating and high-temperature heat pumps, with the latter still under development [152]. However, high-temperature processes in the different material industries of relevance to building and transport infrastructure construction, e.g., steel, cement, and chemicals (as input for plastics), are heterogeneous and require modifications to each specific application, which is why the levels of technical maturity vary across applications [150]. Electrification can also take place indirectly, via the use of hydrogen as a reduction agent in steel production or in fuel cells for the transport sector, with the hydrogen being produced via electrolysis [102], [111].

Reaching high shares of electrification in the transportation sector requires a more fundamental transformation than in the other sectors, although rapid development in the area of electric mobility makes the decarbonization of the heavy transport appear less challenging than was anticipated only a few years ago [75], [151], [153], [154].

To achieve the potential for electrification across industrial and transport sectors, there is a need to map electrification and further develop both renewable electricity generation and support infrastructure (such as power networks and storage facilities) as components of a concerted strategy [152], [155].

4.1.4 Carbon capture

Carbon capture and storage or carbon capture and usage (CCS/CCU) is expected to play an important role in helping to decarbonize heavy industry [156]. There are several technical methods for carbon capture that require different degrees of modification to existing production processes and that may be more or less applicable to different industries. Irrespective of the method used for carbon capture, the resulting CO_2 can be compressed, stored underground or used for other processes (e.g., producing renewable methanol, ethanol or other compounds; see the discussion below). There are limits to the tonnage of CO_2 that can be accommodated through utilization. In particular, this applies to the cement industry, as it will not be possible to produce climate-neutral cement without CCS/CCU [157]. However, in most cases, carbon capture technologies will sequester 80%–90% of the CO_2 stream, with the remaining 10%–20% being released into the atmosphere [75].

The implementation of CCS will require an entirely new infrastructure for transport and storage, which remains a major impediment [101]. With new developments, the removal of legal barriers, and the creation of commercial CCS supply chains, such as the Northern Lights project [158], which is part of the Norwegian full-scale CCS project, this situation is about to change [159].

4.2 Abatement measures per material/activity

4.2.1 Concrete and other cement-based products

The cement industry is a significant source of emissions, currently accounting for roughly 8% of global CO_2 emissions [160]. Around 65% of the CO_2 emissions associated with cement clinker production arise from the calcination process, with the remaining 35% emanating from the fuels used in the cement kilns [161]. Cement clinker production is responsible for the majority of GHG emissions related to concrete use [94], [162]. In addition to concrete, cement is also used in large quantities in mortar to bind bricks and blocks, screed to cover floors, cement-bound boards, and in renders and plasters used to cover wall surfaces [101], [163].

The different cement types are classified based on composition, specifications and conformity, where the Ordinary Portland Cement (OPC) or CEM I has a high share of cement clinker and, therefore, a strong climate impact [164], [165]. The main current emission abatement options regarding cement involve: reducing the amount of cement clinker by using cement clinker substitutes (i.e., waste-based or natural supplementary cementitious materials); reducing the binder intensity (amount of cement or cement substitutes) in concrete; and replacing fuels in the cement manufacturing process with waste-based or bio-based fuels [166].

Cementa AB, which is the only cement producer in Sweden, is a frontrunner when it comes to alternative fuels with biofuels and waste-based alternative fossil fuels (e.g., plastic waste, tires, and solvents), which together made up around 70% of the fuels used in its kilns in 2017 [167].

In contrast, Sweden lags behind the rest of Europe in using cement clinker substitutes (SCMs). While the average share of clinker in cement in European plants is 73% [168], Swedish cement production has an average clinker content of 86% [161]. This can be attributed to regulations, national standards and norms historically being more restrictive [53], [169]. The adoption of concrete with cement clinker substitutes is a key measure requiring further attention.

Despite developments regarding regulations and standards, there has been very limited use of concrete with SCMs in Sweden, particularly in transport infrastructure projects [53]. Several additional barriers have been cited by stakeholders in Mistra Carbon Exit, These range from the easing of standards not being fully applied throughout the technical organization at the Swedish Transport Administration (which needs to provide approval for the use of alternative concrete in projects), through technical challenges associated with production control (particularly in cold weather), potential changes in the properties of the concrete and whether durability can be guaranteed, to economic concerns as to process adjustments with, for example, additional hardening times prolonging project timelines. While these barriers are confirmed by Benhelal et al. [170], other studies including that of Wesseling and Van der Vooren [171] also describe systemic lock-in effects, centered around vested interests, and the lack of a business case for alternatives, noting that coordinated policy efforts are needed with a focus on procurer-supplier knowledge diffusion and market creation support. Nonetheless, we note that cement clinker substitutes are in wide use in transport infrastructure projects in Denmark, Norway and the Netherlands [169], [172], [173] .

The main cement clinker substitutes used currently are: fly ash from coal power production; and ground-granulated blast furnace slag (GGBFS) from steel production [174]. GGBFS requires further processing, such as drying and grinding, which gives it a slightly higher climate impact than fly ash [175], [176]. The achieved strengths of cements that incorporate GGBFS, fly ash or limestone (measured at 28 or 56 days) are similar or higher than those achieved with Portland cement, while the drying time or early strength might be modified [177], [178]. To enhance drying, the concrete should be covered in the first days after casting, and for higher levels of clinker substitution, it may be necessary to adjust the production planning accordingly, at least when the concrete curing temperature is far below 20°C [178], [179]. Finer grinding of aggregates can also help to improve the early strength development [168].

Regional availability and increased prices due to increased competition impose limits on implementation, whereby clinker content in cement of around 50% and 60% are seen as feasible European and global averages, respectively [180]. In the Swedish perspective, current GGBFS production from the Swedish steel industry is about 450,000 tonnes per year, which corresponds to around 15% of domestic clinker production [157]. A new production facility for GGBFS started production during 2020 and is processing blast furnace slag from one of two Swedish integrated steel plants [181]. If all the GGBFS from Swedish steel production was used for cement production, the clinker content could be reduced to 73% [157].

However, the available amounts of the main cement clinker substitutes used at present are likely to decrease as coal power production is phased out and blast furnaces for primary steel production are converted (while it is not yet clear whether slag from new production methods will still have potential as clinker substitutes [182], [183]). Consequently, the use of alternative SCMs, such as agricultural ashes and calcined clays, will need to be scaled up [115], [168], [180], [184]. There is strong potential for large-scale reduction of CO_2 emissions through extensive use of clays, which are widely available worldwide [94]. Calcined clays require an "activation" treatment (thermal or mechanical), which means that there could be some CO_2 emissions associated with their production [168]. This may, however, be offset by their high reactivity, which allows high levels of substitution. Indeed, 50% (or even up to 65%) of the clinker in cement can be substituted with calcined clays in combination with limestone [115], [168], [185], [186].

Limestone-calcined clay cement also has the advantage that it can be produced in existing cement plants and may reduce production costs by 15%–25% [163], [186]. Furthermore, it does not require major changes to the concrete technology, and has no durability downsides [163], [185]. It is noteworthy that the early strength of concrete with limestone-calcined clay is superior to that of binary systems, due to the alumina phase causing vigorous reactions during the first 7 days of curing [186].

Regarding the optimization of concrete recipes, there is often 20%–30% more cement in the concrete mix today than what is required by the standards. This occurs for two reasons: 1) over-specification of cement by concrete producers, which can be explained by the fact that concrete producers want to reduce risk and have an error margin; and 2) setting higher exposure classes for the concrete than the situation demands [101], [113], [168], [187]. The over-specification can be managed by modifying production to achieve the same strength of concrete with a lower cement content, with the key concept being 'binder intensity'. The binder intensity specifies how much cement is used for every unit of concrete (cubic meter, m^3), to generate a given compressive strength.

Today, the average binder intensity globally is 12 (kg of cement per m^3 and megapascal, MPa), while with good current practice, a binder intensity of 8 is achievable [101].

Regarding higher exposure classes for concrete, one of the main reasons is that logistics and procurement are easier when using the same, high-level class throughout, while for a house, the exterior concrete and the interior concrete are not subject to the same constraints [101], [168], [185]. Digitization of construction will play a crucial role in allowing for more variation in the class of concrete used, and to track the binder intensity of the cement used [101].

In Sweden, an additional issue is that faster construction processes have led to stringent drying requirements, e.g., for slabs covered with plastic or parquet flooring concrete, where very high cement contents are used. As a result, the average cement/binder content of concrete is higher in Sweden than in other countries, with around 420 kg binder per m^3 concrete, as compared to an average 400 kg binder per m^3 concrete in Europe overall [80], [188], [189]. There is, thus, a large potential for the cement demand to be reduced by changing construction production planning to suit new cement types, adjusting concrete recipes depending on the specified flooring, and adding a screed layer or applying floating flooring solutions to create a buffer zone between the concrete and flooring [190], [191].

Using granular optimization with the support of higher quality aggregate and fillers, it may even be possible to reduce the binder content by around 50%, implying a binder intensity of 5 kg cement per m^3 and MPa [101], [168]. However, reducing the binder intensity of concrete to these levels requires changes to the production protocol and the adoption of more-advanced techniques for the blending and processing of the concrete [101].

Other prominent current abatement options for concrete include design optimization to slim down constructions, increased prefabrication to reduce waste and minimize construction process emissions, and material substitutions towards wood-based solutions [101], [163], [180].

The development of smart design, material optimization and construction solutions that use concrete more efficiently and optimization based on function gives a direct saving when a smaller amount of concrete needs to be manufactured and transported [14], [108], [114], [116], [192], [193]. In terms of the volume of concrete used, infrastructure-related structures are generally well-optimized in relation to load, which is rarely the case with building construction [168]. While potentially an over-estimation, Basbagill et al. [97] have proposed that optimizing key parameters in the building, such as the thicknesses of piles and footings, as well as external and internal walls could account for a 63%–75% reduction in the total embodied emissions impact of the building. Developments in prefabrication with digitization of production also provide ever-better opportunities for constructive optimization [50], [168].

As precast elements are made in a more controlled environment with greater precision than in situ concrete, designers can use the materials more efficiently as well as produce more complex parts, such as 'voided' slabs [98], [163]. Moreover, the volume of waste generated by precast and prefabricated structures is lower, by well over 50% in most cases [127]. However, to allow for using less cement, the precast industry will have to develop skills related to cement substitution, as today the use of Portland cement is preferred to ensure rapid demoulding [50], [101], [163].

Several studies have shown that buildings with wooden structures require less energy and emit less CO_2 during their lifecycle than buildings with other types of structures (for reviews, see [11], [37], [38], [41], [194]). While timber has a strength parallel to grain similar to that of reinforced concrete, timber has a low density compared with conventional structural materials, leading to lighter structures [195]. Buildings with a wooden frame still require a concrete foundation to provide the load bearing capacity. However, as a wooden frame reduces the mass of the building, and therefore the loads on foundations, the lighter wooden structures provides the potential to reduce the thickness of the concrete foundation [196]. On the other hand, using wood as a structural material often has the consequence that other materials are introduced to achieve certain performance requirements, including coated gypsum boards for fire resistance [195]. A structural core of timber entails on average 10% of the weight of a similar structure made of concrete, but requires an additional 7% fire-resistant plasterboard, based on data published previously [179], [197]–[200].

Notable in this regard is also the longevity of structures, where concrete structures can be dimensioned for 100 years, for instance, in accordance with tried and tested standards and experience, while there are greater uncertainties associated with solid engineered wooden structures with a similar life-cycle perspective [201].

Depending on its level of exposure to air, all cement-based materials take up some level of CO2 throughout the entire life cycle via a slow natural chemical called carbonation.[202]. However, while concrete structures thus reabsorb some of the embodied CO_2 during use if exposed to air, this predominantly happens at the end-of-life phase [203]. Stockpiling crushed concrete for a longer time at end-of-life will increase the carbonation uptake, but may not be practical due to space constraints [204]. Overall, the effect of carbonation of post-use concrete is thus small and has not been taken into consideration in this thesis work.

Additional abatement measures include the reuse of concrete elements, the recycling of concrete or cement fines, and the use of advanced concrete with binders other than cement. Concrete elements can be reused in other structures and concrete can be recycled in the form of crushed concrete replacing aggregate. However, low demolition rates and other challenges imply a limited overall abatement potential, corresponding to around 5% of "new" concrete [205]. The recycling of cement fines from demolition to replace part of the limestone in cement clinker production suffers from the same limitation of supply, while additionally requiring high-quality separation of demolition waste into coarse aggregates, sand and cement matrix [168].

Furthermore, while advanced concretes made from, for example, geopolymer cement, calcium sulfo-aluminate, alkali-activated or magnesium-based cements, can provide deep CO_2 emissions reductions compared to Portland cement clinker, issues associated with availability, cost of the materials, and technical limitations mean that it is estimated that globally no more than 5% of cement will be replaced by these alternatives by Year 2030 and 10% by 2050, restricted to areas with a local supply [94], [185].

Even if all the current abatement options are combined to their full potentials, transformative technologies are still required to reach the goal of close-to-zero or net-zero emissions in the cement industry by Year 2045. Carbon capture and storage technologies (CCS) with or without electrification of the cement kilns are the key alternatives for deep decarbonization. The Swedish cement industry roadmap targets climate neutrality by Year 2030, with the main focus being on biofuels together with CCS [161]. Cementa has also been pursuing electrification together with Vattenfall through its CemZero project, with a pre-feasibility study released in 2018 [206].

We note, however, that in its most recent update, Cementa reports that although electrification of processes can be a possible solution in the long term, the current focus is on more mature technologies for CO_2 capture [207]. Indeed, even with electrification or the use of biomass to abate the energy-related emissions, process emissions remain, and CCS still needs to be applied. However, the electrification serves to purify the flue gas streams, which facilitates CO_2 capture.

With regard to CCS, there are two main options. CO_2 can be either captured after being generated in the cement kiln (post-combustion capture technologies) or purified from kiln flue gases by applying combustion with oxygen instead of combustion in air (oxy-fuel capture technologies) [184], [208]. Post-combustion capture technologies do not require fundamental modifications to be made to cement kilns and could be applied to existing facilities, provided there is enough physical space available onsite. These technologies include the scrubbing of CO_2 in flue gases using solvents such as amine solutions or the capturing of CO_2 via a calcium looping cycle using lime-based sorbents [180], [209]. Oxyfuel combustion requires more or less a new plant, as well as an air separation unit (ASU) for the production of oxygen [208], [210].

Applying carbon capture exclusively in the precalciner has a higher technical maturity than applying carbon capture in the cement kiln. While the capture rate is lower, at about 60%, it provides an important early capture opportunity and has the potential to reduce the energy penalty associated with capture, due to the use of waste heat recovery [180], [208], [211]. Implementing carbon capture technologies in both the precalciner and the kiln would typically promote 85%–90% avoidance of onsite CO_2 emissions [209], [212].

Oxyfuel capture technologies require process modifications but are, in general, expected to have lower energy consumption and costs than post-combustion capture using scrubbing technologies [209], [213], [214]. However, while some demonstration plant projects involving post-combustion capture with amine scrubbing are underway, for example in Norway [215], both calcium looping and oxyfuel technologies are still at the early development stage when it comes to cement application (oxyfuel has been tested at pilot scale in a power plant application) [216]. Further details and analyses of the emissions, energy and cost implications for the Swedish cement industry can be found in a recent technical report by Karlsson et al. [67].

Table 2 provides an overview of the emission reduction measures for cement and concrete described in literature together with the described abatement potential and time aspect of implementation. As can be seen, measures available at present, within current standards and regulations, may provide abatement potentials up to around 50%, while deeper decarbonization requires standard modifications to allow for higher levels of SCMs or advanced concrete, or the implementation of CCS.

Table 2. Overview of emissions reduction measures for cement and concrete described in the literature, together with the described time aspect of implementation (if available). The reduction potential is compared to the reference GHG emissions intensity for average construction concrete, based predominantly on Portland cement.

Emissions reduction measures	**Reduction potential identified**			**Time of implem-entation**	**Additional references**
Optimize the use of space in residential buildings	**7%–13%** [79]			Present–	
Use of wood as structural building construction material	**5%** [101] **6%–9%** [79] **5%–10%** [217]	**22%** [218] **32%** [219] **34-69%** [196]	**9%–48%** [194] **42%–61%** [38]	Present–	
Use of alternative bridge construction materials (e.g., wood, composites)	**9%** Timber [220] **19%–31%** Timber [221]	**34%** Soil-steel composite [222]	**48%** Composite [223]	2025/2030–	
Reuse of concrete elements	**4%** [101] **2%–8%** [79] **9%** [75]	**10%–20%** including cement recycling [168]	**(10%–50%)**; Only prefabricated elements [79]	2025–	
Reduced binder intensity – use of optimized concrete recipe	**4%–9%** [53] **10%** [163]	**4%–16%** [79] **20%** [168]	**26%–33%** [101]	Present–	
Reduced over-specification of concrete – adherence to standards	**2%–9%** [79]	**9%** [168]	**11%–18%** [101]	Present/ 2025-	
Design optimization – slimming of constructions	**10%** [75] **10%** [163] **11%** [224] **10%–12%** [79]	**13%** [101] **14%** [225] **15%** [53]	**30%** including recipe optimization [192] **33%** [115] **20%–40%** [168]	Present /2025–	[115], [226], [227]
Precast/prefabricated concrete	**3%** [121] **3%–4%** [129]	**8%** [98] **8%–11%** [79]	**14%** [115] **16%** [129]	Present–	[228]
Concrete with traditional cement clinker substitutes (e.g., limestone, fly ash, granulated blast furnace slag, GGFBS) according to current standards (≤35%)	**8%–10%** 20% GGBS [53] **9%–35%** [229] **13%–15%** Fly ash [162] **8-15%** 35% Fly ash [53]	**12-21%** 35% GGBS [53] **22%** GGBS [162] **23%** 6%–20% Fly ash [230] **24%** 34% [166]	**25%** 35% Fly ash [175] **26%** 20% Fly ash [231] **38%** 33% GGBS, 5% Ground lime [232] **41%** 35% Fly ash, 5% ground lime [233]	Present–	[180], [220], [227], [234], [235]

Emissions reduction measures	Reduction potential identified			Time of implem-entation	Additional references
Concrete with traditional cement clinker substitutes outside current standards (>35%)	**37%** [180] **45%** 30% fly ash, 30% GGBS [175]	**48%** 55% GGBS, 5% Ground lime [236] **61%** 67% GGBS [237]	**66%** 73% GGBS [238] **62%** 80% GGBS [176]	2025/2030–	
Concrete with non-traditional waste-based cement clinker substitutes	**11%** 10% EAF steel slag [229]	**40%** Calcium carbide residue [208]	**42%** Calcium carbide residue [166]	2025/2030–	[184], [234]
Natural cement clinker substitutes	**20%** Pozzolan [239] **20%** Barley/rice husks [240] **40%** 30% Fly ash, 10% silica [175] **47%** 14% Silica, 8% Fly ash [176]	**10-27%** Calcined clay [163] **27%** Calcined clay [241]	**38%**; 50% Calcined clay [186] **40%** Calcined clay [185], [242]	2025/2030–	[115], [184], [234], [242]
Advanced concretes	Geopolymer: **9%** [243] **34%** [166] **44%–64%** [244] **45%** Fly-ash based [245]	**52%** [246] **54%** [247] **66%** [208]	**47%;** 70% Alkali-activated, 30% GGBS [248] **55%–75%** Alkali-activated [249] **85%** Magnesium oxide-based [208]	2030/2045	[180], [250]–[253]
Recycling of cement fines	**6%** [75]	**5-7%** [79]		2030/2045	[168]
Biomass cement plant fuel substitution	**7%–30%** Biological sludge [254] **6%–10%** Agricultural residues [170]	**10%** 40% Meat and bone meal [255] **10%–12%** [180] **10%–15%** [234]	**20%** [161] **21%–28%** Sewage sludge [256]	2025/ 2030–	[166]
Wastes as cement plant fuel substitution	**3-5%** 30% [257] **6%** [258] **1-9%** [259]	**3- 9%** 50% Tires [260] **4-11%** [234]	**12%** 30% refuse-derived [254] **20%** Tires [261]	2025/2030–	[166]
CCS to capture cement plant CO_2 emissions	**45%** [161] **32%–48%** [234] **48%** [180] **39%–78%** [166]	**60%–72%** Oxy-combustion/chemical-looping [261] **65%–90%** Partial/full oxy-combustion [262]	**89%–99%** Oxy-combustion/chemical-looping [211] **76%–100%** Oxy-combustion/ chemical-looping [210]	2030–	[212], [263]–[265]
Electrification of cement production	**32%** [266]	**33%** [267]	**54%** [102]	2030/2045	[161]

4.2.2 Steel production and use

Manufacturing steel produces a lot of GHG emissions, equating to around 8% of global CO_2 emissions [268], [269] or around 25% of construction-related CO_2 emissions [114]. Primary steel from iron ore is mainly produced in integrated steel plants via the blast furnace/basic oxygen furnace (BF/BOF) route, with an average European emissions intensity of 1.9 tCO_2 per tonne of steel, as compared to 0.4 tCO_2 per tonne of steel when produced from scrap steel in secondary steelmaking plants, i.e., electric arc furnaces (EAFs) or mini-mills [101], [270], [271]. Downstream metallurgic processes, i.e., casting and rolling into sheets, plates, rods/bars and sections, contribute another 0.1 tCO_2 per tonne of steel product [101]. Construction steel, which is often galvanized, is predominantly produced from primary steel, while reinforcement steel is mainly produced from scrap steel, although this varies globally depending on the availability of scrap steel [271].

Whether primary or secondary steel is used in steel production partly depends on the type of metallurgy or processing needed. Primary steel is more malleable that scrap steel produced in EAFs, which is why it is often used in products that involve a large degree of cold working. EAF-produced steel is instead used to make structural beams, plates, rebar and other products that require little cold working. For steel coils, used in metal sheets for construction, close to 100% were produced from primary steel in 2008 [272]. The ratio of hot-rolled to cold-rolled sheets is about 70/30, indicating that more could be produced from scrap steel. More recent figures from the US reported by Zhu et al. [273] suggest a ratio of 80/20, with the slabs used as intermediate products generated from primary/secondary steel having a ratio of hot-rolled to cold-rolled sheets of about 50/50.

While integrated steel plants require coal as both a reducing agent and fuel, EAFs mainly use electricity, supported by natural gas (25%–30%) and sometimes coal (<5%) [270], [271], [274], [275].

Overall, enhanced material efficiency and circularity measures are the important current abatement options to reduce embodied emissions associated with steel [75], [101], [115], [276]. The main opportunities lie in: reducing waste during the construction process; reducing the amount of material in each building by avoiding over-specification and using higher-strength materials; and reusing buildings and building components. Studies have demonstrated that 35%–45% of steel used in construction is in excess of what is necessary to achieve the desired structural strength [75], [114], [118].

With better sorting and separation, there is a potential to increase the scrap share in primary steel production, as well as to shift towards higher levels of steel production in EAFs [75], [104]. In 2013, about 85% of all scrap from construction steel was recycled globally [30]. While the current availability of steel scrap is not sufficiently high to meet the full demand for steel products [196], scrap availability is expected to increase the ratio of steel produced in EAFs from the current level of 40% in Europe (25% globally) to up to 70% by Year 2050 in Europe (50% globally) [75], [101].

In the mid-term perspective, bio-based fuels and reducing agents (charcoal or biocoke) represent feasible options to mitigate GHG emissions [277] in modern integrated steel plants. There are various ways to incorporate biomass into the BF/BOF route, including: substituting pulverized coal with biocoal in the blast furnace; replacing coke/oil with biofuel for sintering/pelletizing of iron ore; partly replacing top-fed coke into the BF with biocoke; and partly or fully replacing nut coke with biocoke [270], [277], [278].

The biomass substitution technologies are at different stages of development, with substitution of pulverized coal with biocoal being the most feasible and promising in the near term. Depending on the pulverized coal injection (PCI) rate of a blast furnace, this would imply an emissions reduction potential of 18%–40%, where higher PCI rates yield larger CO_2 reductions [279].

Further CO_2 emissions reductions are difficult to attain without introducing drastic changes to the technologies. The technologies with potentials for deep emissions cuts include top-gas recycling blast furnaces (TGR-BF) with carbon capture, different smelting technologies, electrowinning, and using hydrogen as reduction agent instead of coke [265].

Regarding carbon capture, a major problem associated with implementing carbon capture in integrated steel mills is the number of different point sources [213]. The largest single point source is the blast furnace, from which 65% of the emissions can be captured, with the coke plant and sinter plant accounting for 27% and 6% of the overall emissions, respectively. Partial CO_2 capture from blast furnace gases based on amine absorption of CO_2 is a mature and low-cost technology that can be implemented in the coming 10–15 years without major changes to the existing process being needed, and this can be combined with biomass substitution [280]–[282].

The main technical option that has been explored for deeper emissions reductions via carbon capture is top-gas recycling in the blast furnace in combination with CCS. TGR-BF is currently in the demonstration phase and involves the injection of oxygen (rather than enriched air) into the blast furnace. The top gas is subsequently recycled after separating the CO and CO_2 via an absorption process. A TGR-BF unit with CCS could reduce the CO_2emissions of the steelmaking process by 50%–60% [283]–[286].

Electrowinning, i.e., electrolysis of iron ore using electricity, is a rather immature technology, where the iron ore is either dissolved or suspended in an acid or alkaline solution or melted in a saline solution for high-temperature electrolysis (above 1600°C) [102], [287].

A more indirect route to electrification would be to use hydrogen, produced via electrolysis, as the reducing agent in a direct-reduced iron (DRI) process, which is a process that is currently used with natural gas as the reduction agent [102], [285], [288]. This route could also be utilized for energy storage or load smoothing in the electricity grid if implemented in a smart way [102]. For all of these, wider adoption is unlikely before Year 2030 [284]. In the case of Sweden, the vision of complete decarbonization of the iron and steel industries is shifting towards the indirect electrification option, where iron ore is reduced directly in a solid state by the addition of hydrogen (produced with renewable electricity) as a reduction agent in a shaft furnace [288]–[290]. This concept is developed within the so called HYBRIT joint venture, which aims to have a full-scale demonstration plant with a capacity of 1 million tonnes of steel in operation by 2025. The goal of the joint venture is to be able to introduce fossil-free steel to the market already by 2026, with full conversion to 2035 [291].

For secondary steel production in EAFs, electricity is the main energy carrier, making the emissions intensity of the electricity used an important factor [113]. Indeed, reinforcement steel produced from scrap with low-emission electricity, thereby reducing the associated GHG emissions significantly, is already available in the market, although the availability of such reinforcement steel is limited.

Thus, lack of access to such products in the short term may prove to be a barrier, and increased demand for this type of steel also runs the risk of disturbing the market with higher prices as a result.

On a general level, decarbonization of the electricity grid will greatly affect the emissions intensity of steel produced in EAFs [113]. The Nordic electricity grid already has a high share of low-carbon energy sources (predominantly hydro, nuclear and wind), providing for a carbon intensity under 60 gCO_2/kWh, compared to the global average of over 500 gCO_2/kWh [292].

For process energy, biomass could substitute for fossil energy also in EAFs, both as a reducing agent and as fuel in reheating furnaces [293], [294]. The potential for fuel substitution reported in the literature varies, ranging from around 60% to 100% of the chemical energy use [270], [277], [278], [293]. Substitution of natural gas with bio-based syngas or bio-oil has similarly been proposed for metallurgic processes handling both primary and secondary steel, i.e., casting and rolling [295].

Another aspect to take into account is that only 4% of Swedish-produced steel is used in Swedish construction, with the vast majority of construction steel being imported [119]. The fact that steel is traded on a global market has frequently been pointed out as a barrier to realizing its emission reduction potential (see, for example,[296]–[298]). In terms of construction steel, current steel producers have highly specialized product portfolios that are sold on a highly competitive market, which is why policy measures and investments geared towards transformation of the steel sector to allow for low-carbon construction steel will be needed at least on the European, if not on the global level [299]. Various measures have been put forward to manage this transformation, including industrial R&D support, piloting of net-zero technologies, and demand support such as border carbon taxes, consumption-based carbon pricing, and/or cross-sectorial collaborations.

Bataille et al. [300] have stated that each region needs a heavy industry decarbonization pathway focused on its particular competitive (dis)advantages and potential markets, e.g., reflecting access to biomass, zero-carbon electricity and heat, and geologic storage for CO_2. Further details and analyses of the emissions, energy and cost implications for the Swedish steel industry, which are deemed relevant to developments also on a European level, can be found in the recent article and technical report of Toktarova and colleagues [68], [301].

An overview of the emission reduction measures for construction and reinforcement steel described in literature together with the indicated abatement potential and time of implementation is shown in Table 3. From the indicated measures and potential, we can see that material efficiency measures are key abatement measures in the short term, while CCS or electrification technologies are needed to reach deep decarbonization levels.

Table 3. Overview of emissions reduction measures for construction and reinforcement steel described in the literature, together with the described time aspect of implementation (if available). The reduction potential is compared to the reference GHG emissions intensity for construction steel (structural steel sections or light steel sheets) produced from iron ore in an integrated steel plant and reinforcement steel produced from secondary steel (scrap-based steel), both including metallurgy (i.e., casting and rolling).

Emissions reduction measures	**Reduction potential identified**		**Time of implem-entation**	**Additional references**
Material efficiency (overall)	**12%**; to 2050 [302]	**24%**; to 2045 [193]		
Structural optimization - reduced over-specification of reinforcement steel	**3%–22%**; cutting losses [303] **10%–12%** [79]	**10%–15%** [304] **15%–30%** [114]	Present/2025 –	
Structural optimization - reduced over-specification of structural construction steel	**13-24%** [193] **15%** [115] **19%** [117] **36%** [305]	**37%** [79] **35%–45%** [114] **46%** [306] **30%–50%** [101]	Present/2025 –	
Reuse of structural steel elements	**6%** [75] **13%** [193] **15%** [117]	**38%** [79] (**50%–80%**; including increased scrap-ratio [79]	2025/2030–	[114]
Prefabrication	**18%/32%**; non-steel/steel frames [193]		Present–	
Reinforcement steel produced with low-emission electricity	**5%–27%** [53] **31%** [307]	(72%; compared to rebar produced with a combination of primary and secondary steel [113])	Present–	[53], [307]
Increased scrap-ratio for construction steel	**10%–20%**; overall primary steel [75], [104] **32%;** steel sections: 85% scrap- based steel [308]	**47%**; steel sections: **74%** scrap-based steel [309] **70%**; steel sections: **100%** scrap-based steel [310]	Present/ 2025–	

Emissions reduction measures	Reduction potential identified		Time of implem-entation	Additional references
Biomass fuel substitution in integrated steel plants	**10%** [270] **7%–15%** [311] **17%–23%** [312]	**30%** [313] **20-41%** [314] **31-57%** 25-37% BF only [294]	2025/2030–	[277], [315]
Partial carbon capture in integrated steel plants	**19-30%** [209], [316], [317]	**38%** [318]	2025–	[281], [282], [319]
Full carbon capture in integrated steel plants (e.g., combined with blast furnace top-gas recycling, TGR)	**60%** TGR w CCS [283] **50%** TGR w CCS [284] **56%–62%** TGR w CCS [285] **60%** TGR w CCS [286]	**55%** ULCORED[1] with CCS [284] (**80%** HISarna[2] with CCS [284])	2030/2035–	[101], [251], [313]
Hydrogen direct reduction (H-DR)	**70%** [266]	**53-91%** H-DR: current EU electricity emission factor/zero-emission electricity [285]	2045	[75], [101], [102], [251], [275], [313], [320], [321]
Biogas/biocoke in secondary steel production heating ovens	**7%–21%** Bio-based syngas [278] **6%–11%** 50-100% biocoke [294]	**28%** Biogas and biocoke [293]	2025/2030–	[312], [313]
Biomass in steel metallurgy	**10%** [322]		2025/2030–	[278], [295], [313]

[1] ULCORED is a direct reduction process using either natural gas of gas from coal gasification as a reduction agent.
[2] HISarna is smelting reduction process using pure oxygen in a combination of a hot cyclone and a bath smelter.

4.2.3 Aluminum

Aluminum is either rolled into plates, sheets, strip and foil or extruded into sections, tube, rod bar and wire, with rolled aluminum having a climate impact that is about 30% lower than extruded aluminum [323]–[325]. This is partly due to differences in scrap rates, as secondary aluminum reduces the climate impact by around 90%–95% [326]–[328]. The current average scrap-rate in aluminum production is 20%–50% (including fabrication scrap) [114], [329]–[331], while Allwood and Cullen (2012) [114] have reported that the share of secondary aluminum used in construction is significantly lower, with primary aluminum being around 95% of the input for extrusion and rolling. Therefore, increased scrap rates represent prominent abatement measures for aluminum [116], [331], [332].

As the production of primary aluminum is electricity-intensive [328], [330], [333], [334], the GHG emissions intensity of the production is closely linked to the emissions intensity of the electricity production [276], [335]. Additional GHG emissions arise from the use of coal and natural gas in electrolysis, smelting and processing, along with process emissions from the use of cathodes [328], [334], [336]. Other abatement measures, accordingly, include electrification or firing of syngas in alumina refining [266], bio-charcoal or biogas replacement of coal as the reduction agent [276], [334], and the use of biogas of biogas in processing [334], as well as electrification opportunities via plasma heating for secondary aluminum production [152]. Inert anodes can also reduce the process emissions associated with aluminum production [216], [251], [336].

There are also carbon abatement opportunities in the area of material efficiency and demand reduction [193], [298], [337]. Details of the key emission reduction measures for aluminum described in literature are exhibited in Table 4.

Table 4. Overview of emissions reduction measures for use of aluminum in buildings described in the literature, together with the time aspect of implementation (if available). The reduction potential is compared to the reference GHG emissions intensity of primary aluminum construction products.

Emissions reduction measures	Reduction potential identified		Time of implement-ation	Additional references
Material efficiency	**2%–13%**; to 2050 [193]	**15%–24%**; to 2050 [75]	Present/2025–	[298], [337]
Increased scrap rate	**57%** [276] **60%** [325]	**66%** [331] **77%** [338]	Present/2025–	[116], [332]
Low-carbon electricity in primary aluminum production	**53%** [339] **70%** [276]	**80%** [298]	2025/2030–	[335]
Fuel substitution in primary aluminum production	**4%**; Biogas in processing [334] **11%**; Biogas/Syngas in alumina refining and melting [266]	**17%**; natural gas [276]	Present/2025–	

Emissions reduction measures	Reduction potential identified	Time of implement-ation	Additional references
Inert anodes in primary aluminum production	**14%** [336]	2030–	[216], [251]
Electrification of secondary aluminum production	**4%–5%** [152]	2030–	

4.2.4 Insulation

At present, polystyrene-based insulation [expanded polystyrene (EPS) and extruded polystyrene (XPS)] together with mineral wool (rock/stone wool and glass wool) are the most frequently used for insulating buildings [340], with alternatives including phenolic foam, vacuum insulation panels and insulation based on natural fibers [341]–[344]. The climate impact of polystyrene-based insulation can be improved by introducing a share of graphite [345]. In comparison, mineral wools generally have a lower carbon footprint and primary energy demand [11], [92], [342].

For insulation materials to be comparable without needing to redesign the constructions, their thermal conductivities need to be equivalent, yielding a specified insulation performance [341], [342]. To acquire a specified insulation performance with equivalent thickness, both the density and thermal conductivity of the material are of relevance [341], [346].

While insulation composed of natural fibers, such as wood fiber, cellulose, cork and hemp [108], [347], most often entail lower embodied emissions, the natural insulation materials currently available on the market have higher thermal conductivities than mineral wool or polystyrene, necessitating a thicker insulation layer [347], [348]. As the building codes in the Nordic countries require very low insulation values, the use of cellulose or wood fiber would lead to extremely thick wall constructions, potentially reducing daylight penetration, making these a less-pertinent solution, at least for external facades [179], [348]. Going forward, the use of natural resins such as lignin, to produce high-performance insulation materials, e.g., replacing phenolic resins in phenolic foam insulation, could represent a potent abatement option [349].

However, it is also worth noting, as reported by Zabalza Bribián et al. [92], that there is a certain inertia inherent to the use of conventional insulation, with established commercial networks and skepticism among designers making it difficult for natural and/or recycled insulation materials to compete [92].

Indeed, the introduction of recycled materials into the product composition is a high-potential option to improve the environmental performance of mineral wool insulation [50], [346], [350]. Mineral wool production requires high-temperature furnaces, which are often fueled by oil or natural gas [100], and rock wool production requires a certain level of consumption of coal to fuse the basaltic rock [92]. However, both the production technology and energy mix differ from country to country, whereby products produced in EAFs reduce the emissions intensity significantly [351]–[354], particularly with the use of low-carbon electricity [355].

Fuel changes (including electrification) together with energy efficiency measures are key abatement measures for the production of both mineral wool and polystyrene insulation [100], [101], [353], [356]. Regarding polystyrene, abatement options that are pertinent to plastic production are also of relevance, as around 70% of the climate impact of polystyrene-based insulation stems from the raw material [346].

An overview of the various emission reduction measures detailed for insulation materials in literature is shown in Table 5. This displays both the abatement potential linked to material substitution as well as emissions reductions measures available regarding the material production for the most common insulation materials.

Table 5. Overview of emissions reduction measures for use of insulation materials in buildings described in the literature, together with the time aspect of implementation (if available). For material substitution measures, the reduction potential is compared to the reference GHG emissions intensity for polystyrene-based insulation. For specific material production measures, the reduction potential is compared with the reference production for the specific insulation material.

Emissions reduction measures	Reduction potential identified	Time of implement-ation	Additional references
Material substitution – polystyrene with graphite	**24%–52%** [357]–[359]	Present–	[345]
Material substitution – alternative conventional insulation materials (glass/rock wool and phenolic foam)	**32%–75%**; mineral wool [92], [97], [342] **55%;** phenolic foam [343], [360]	Present–	[346], [361]

Emissions reduction measures	**Reduction potential identified**	**Time of implement-ation**	**Additional references**
Material substitution – alternative non-conventional insulation materials (cellulose, wood chips, cork, hemp, flax)	**63%–94%** [92], [97], [100], [342], [362]	2025–	[346]–[348]
Glass wool produced from recycled glass	**30%** [342], [356] **37%** [174]	Present–	
Low-density rock wool insulation material	**53%** [341] **65%** [363], [364]	Present–	
Recycled material in rock wool production	**28%**; 25% recycled rock wool [350]	Present–	
Energy efficiency and fuel change for mineral wool production	**12%** [356], [365] **7%–14%**; Oxyfuel cyclone furnaces [353]	Present /2025–	
Electrification of mineral wool production	**50%** [355] **50%** [354] **72%** [353]	Present–	
Biofuel substitution in mineral wool production	**20%**; 40% substitution from coke to biochar [353] **18%–27%;** Biogas substitution from natural gas [353]	2025–	
Natural resins for phenolic foam insulation	**34%–80%**; [343], [349]	2025/2030–	
Energy efficiency and fuel change for plastic and EPS/XPS[1] production	**21%–44%** [101], [346]	2025–	
Recycling of polystyrene in EPS/XPS	**19%–23%**; 20% recycling [350]	2025/2030–	
Electrification of EPS/XPS production	23-26% [346]	2030–	
Electrification/CCS on cracking and/or polymerization in plastic production for EPS/XPS production	**22%–27%**; CCS/electrification in cracking [101], [103], [321] **39%–42%**; CCS/electrification in cracking and polymerization [101]	2030–	[75], [102]

[1] EPS stands for expanded polystyrene and XPS for extruded polystyrene, both being polystyrene-based insulation materials.

4.2.5 Plastics

Plastics has many applications in building and construction sector, being used for thermal insulation, pipes, floors, and finishing, among other purposes [366]. Plastics are made from fossil oil and gas, produced predominantly through steam cracking of naphtha and ethane, which are obtained by refining crude oil and from natural gas, respectively. Indeed, steam cracking is responsible for a large share of its carbon footprint (~40%), combined with feedstock production, refining, polymerization and blending [101]. Improved efficiencies in the refining, cracking and polymerization steps could be achieved through enhanced catalytic processes or advanced membrane separation [103], [365]. Deep abatement options for plastics production otherwise include electrification of the cracking and polymerization processes [102]. Another alternative is to fit carbon capture and storage or use (CCS/U) to current processes. To reach a deep abatement level, however, carbon capture would need to be applied not just to fit the core steam cracking process, but also to refining so as to capture CO_2 upstream (and for end-of-life incineration plants to capture CO_2 downstream) [101].

However, plastic can also be recycled, rather than incinerated, either by mechanical or chemical means [75], [115], [321]. There are also developments around alternative bio-based or synthetic feedstocks [321], where the fossil feedstock is replaced by a combination of renewable hydrogen, syngas and renewable (or recirculated) carbon [102]. The process is based on hydrogen, which is produced through water electrolysis with low-carbon electricity, followed by hydrogenation of CO_2 as a carbon source [104]. The carbon is derived either from captured CO_2 or as the CO_2/CO part of syngas. The syngas can be produced by gasification or pyrolysis of woody biomass, biogenic waste or waste plastics [102].

A more current abatement option is the reduced use of plastics in key value chains. Through greater materials efficiency in end-products, the demand for plastics in the buildings value chains could be reduced by up to 35% [75], [115].

Table 6 provides an overview of the range of different emission reduction measures described for plastics in literature together with the indicated abatement potential and expected time of implementation.

Table 6. Overview of emissions reduction measures for plastics described in the literature, together with the time aspect of implementation (if available). The reduction potential is compared with the average GHG emissions intensity for polyethylene (PE) and polyvinylchloride (PVC).

Emission reduction measures	**Reduction potential identified**	**Time of implement-ation**	**Additional references**
Material efficiency	**14-35%** [75], [101], [321]	Present-	
Energy efficiency and fuel change	**15%–40%** [101], [367]	Present /2025–	
Novel catalysts and membranes	**5%–15%** [365] **10%**; membranes [103] **15%–20%** catalytic cracking and energy efficiency [75] **20%**; catalytic cracking [103]	Now/2025–	[321]
CCS for refining	**8%–9%** [101]	2030–	
Electrification/CCS for cracking and/or polymerization	**31%**; electrification on cracking [101] **37%**; CCS on cracking [103] **39%**; electrification on cracking [321] **55%**; CCS on cracking and polymerization [101] **60%**; electrification on cracking and polymerization [101]	2030–	[75], [102]
Methanol to ethylene production	**47%** [103]	2030–	
Plastics recycling	**22%** [103] **56%** [75] **91%–100%** [101]	2030–	[103], [276]
Bio-based/synthetic feedstock	**40%** [101], [321] **47%** [104] **100%** [102]	2030/2045–	[251]

4.2.6 Gypsum and plaster

Plasterboard is a versatile material in modern construction. Made from the simple materials of gypsum and paper, it is used in most building types in a wide range of applications, including wall lining, partitions, sound control and fire protection [368]. Fire-resistant plasterboard, used as fire protection in wood-frame buildings, has an average GHG emissions intensity that is around 35% higher than that of standard plasterboard [369]–[372]. The main environmental impacts associated with plasterboard result from the production process, where both production and calcination use natural gas and electricity.

Compared to cement and lime, however, the calcination processes occur at significantly lower temperatures, usually within the range of 135°–180°C, which is why the levels of fuel consumption and CO_2 emissions from gypsum manufacturing are significantly lower [368].

The most prominent abatement measure for the production of gypsum for plasterboards is the use of recycled gypsum, with studies confirming that it is possible to substitute 100% of commercial gypsum with gypsum waste without any heating treatment [373]. A positive side-effect of gypsum recycling is reduced energy consumption for the fabrication of recycled gypsum [374]. Recycling can be combined with the electrification of biofuel substitution in the heating furnaces used for the production of gypsum [374].

Other abatement options include substituting part of the gypsum in the plasterboards with, for example, cardboard [375] or the use of building boards made of natural fibers, such as hemp, flax or jute [376].

The indicated abatement potential for the key emission reduction measures described for gypsum plasterboard in literature is detailed in Table 7.

Table 7. Overview of emissions reduction measures for gypsum plasterboard described in the literature, together with the time aspect of implementation (if available). The reduction potential is compared with the average GHG emissions intensity for standard gypsum plasterboard.

Emissions reduction measures	**Reduction potential identified**	**Time of implement-ation**	**Additional references**
Recycled feedstock	**58%–65%** [373], [374]	Present/2025–	[377]
Electrification/ biofuel substitution	**25%–85%** [374]	2025/2030–	[365]
Material substitution – natural fibers	**47%–59%** [376]	2025/2030–	

4.2.7 Timber and other forest-based products

Timber is one of three structural materials currently used in the construction of large structures, along with steel and reinforced concrete [195]. Various LCA and review studies have demonstrated that in general, wooden structures require less energy and emit less CO_2 during their lifecycle than buildings with other types of structures (for reviews, see [37], [194], [196], [219], [378], [379]). Resources from forests also provide construction materials used for various other purposes, with products including e.g. flooring, decking, plywood, particleboard and different types of fiberboards [380].

For forest-based products to have a low-carbon footprint [174], the main prerequisite is sustainable forestry, which from the CO_2 perspective implies that the forest carbon stock is maintained [148], [381]. LCA studies, in general, presume that this prerequisite is safeguarded and thus consider forest-based products to be carbon-neutral over their lifecycle [145], [146], [382]–[384]. However, the best way to account for biogenic CO_2 emissions in LCA is widely debated. These discussions relate to two aspects. The first relates to 1) forest management regimes. A large part of the carbon storage in forests takes place in the soil and other vegetation, which can be affected by forestry methods [146], [148], [197]. Secondly, the discussion relates to the temporal aspect of the CO_2 emissions [144], [145], [384]–[386]. While CO_2 persists for a long time in the atmosphere, when regarded in a shorter time perspective, such as national and international climate goals and risks for so-called tipping points for global warming, the timing of emissions plays a role [143].

In this regard, the concept of radiative forcing becomes pertinent. Radiative forcing is the difference between solar irradiance (sunlight) absorbed by the Earth and energy radiated back to space [387]. The radiation balance is altered by changes in the level of GHG in the atmosphere, due to for example the difference between CO_2 release and sequestration. While the net CO_2 emissions may be zero, the net effect on radiative forcing over the short term can be either positive or negative, depending on the time difference between CO_2 release into and sequestration from the atmosphere [143], [144]. Thus, if the release of biogenic CO_2 occurs before the same amount is once again sequestered by replanted and growing trees, the related harvest will have caused a temporary increase in radiative forcing in the atmosphere. Conversely, if sequestration of biogenic CO_2 is seen to occur prior to the corresponding release of CO_2 into the atmosphere, the forest-based products can cause a temporary reduction of the radiative forcing in the atmosphere [145]. Most studies conclude that when timber is used in long-lived products such as building structures it can be considered to act as a temporary carbon sink if the wood raw material comes from a "sustainable" forest in which felled trees are constantly replaced by new trees, forestry practices allow the soil carbon content to remain in balance, and the rotation period of the tree species used is short relative to the lifetime of the building structures [144]–[146], [196], [384], [388].

At a landscape level, the stand-level carbon flows associated with many different stands at different stages of their rotation cycles will be aggregated and produce overall trends [219]. In Sweden , the forest standing stock has nearly doubled over the last century [389], and also on a European scale the forest carbon stock is growing over time [148]. Further, improved forest management and the effects of climate change may lead to substantial increases in forest growth going forward [390], which would increase the long-term future potential of biomass harvest [389]. This provides opportunities to increase use of renewable forest resources as part of a strategy to transition to a more sustainable, carbon-neutral society [219].

In general, review studies recommend that LCA practitioners are aware of the influence of method choice when carrying out studies, use case-specific data (for the forest growth), and communicate clearly how the results can be used [145], [146], [383], [384].

The climate impacts of wood products are also affected by emissions from other elements of the supply chain, such as forestry, glues, and processing [113], [195]. Most of the emissions in the forestry supply chain stem from fossil fuel use by harvester machines and timber transport units [196]. The fuel substitution and other measures discussed in the construction equipment and heavy vehicles sections (see Sections 4.2.11and 0) are thus relevant to this aspect. In the remainder of the supply chain, at least in the Nordic context, electricity use is the main contributor to GHG emissions, implying that the carbon intensity of the electricity supply is of importance [128], [196], [391].

Details of the emission reduction measures described in literature for the timber supply chain, including the indicated abatement potential, assuming sustainable forestry as a prerequisite, is shown in Table 8. Further details regarding engineered wood products are described in the following section.

Table 8. Overview of emissions reduction measures for timber and other forest-based products described in the literature, together with the time aspect of implementation (if available). The emissions reduction potential is compared with the average GHG emissions intensity for sawn timber, assuming sustainable forestry.

Emissions reduction measures	Reduction potential identified	Time of implement-ation	Additional references
Biofuel substitution/electrification in forestry operations	**14%–16%** [391]–[393]	Present/2030–	
Biofuel substitution/electrification (including modal shifts to train) in timber transport systems	**32%–39%** [391]–[393]	Present/2030–	
Open-air drying of wood	**11%** [92]	Present–	
Use of low-carbon electricity in sawmills	**30%–33%** [196]	Present/2025–	

4.2.8 Engineered wood products

For building construction in particular, the development of engineered wood products such as cross-laminated timber (CLT), laminated veneer lumber (LVL), and glued laminated wood (glulam) has enabled increased adoption of construction designs that have a structural core of timber, predominantly for low- and medium-rise buildings [394], with recent examples also of high-rise buildings [195], [196]. Indeed, engineered wood products have recently experienced annual growth rates of between 2.5% and 15% [217], with future penetration levels being highly uncertain, ranging from conservative expectations of 5% substitution of wood for concrete [101] to estimates of 50% and 80% for all new multi-family houses being built with wood in 2025 and 2050, respectively [395], [396] (compared to the current rate of 13% for multi-family buildings built of wood in Sweden [397]). Karlsson et al. [28] in their roadmap to carbon neutrality for the building sector assumed a growth rate of 5%, leading to the share of new multi-family buildings constructed in Year 2045 being close to 60%.

In terms of the impact of upscaling of structural timber on harvesting levels, a recent Swedish study has shown that an annual 2% increase in the share of wood-frame multi-family buildings would correspond to less than half the yearly amount of biomass that Swedish forests can produce in Year 2050 [200]. On the European scale, it has been calculated that if the entire European population was to live in wood-frame apartments, approximately 40–50 million hectares of forest would be required to renew those buildings every 50 years, representing about 25%–30% of Europe's forests, assuming current management and harvest levels [195]. On a global level, however, the annual volume of concrete used in the world is about 10-fold greater than the global forest harvesting rate [398].

The carbon footprint of engineered wood products arises from the timber supply chain (around 50%), combined with transport, processing and production of adhesives [393], [399], [400].

In addition to mitigation measures linked to timber production (as detailed in Section 4.2.7), comparing environmental production declarations for cross-laminated timber demonstrates a potential to reduce the amount of adhesives used [399], [401], [402].

There is also room for improvements related to the replacement of conventional urea or petroleum-based resins with natural resins [349], [403]–[406]. Depending on the quantity of resin used in each product, the equivalent emissions of CO_2 would thus be further reduced. On average, this reduction in emissions of CO_2 is estimated as 16% for laminated wood and 46% for fiberboard [92].

A lighter wooden construction usually requires a less-extensive foundation and, therefore, less concrete [128]. However, it is worth noting that the use of wood as a structural material often has the consequence of introducing other materials to achieve specific performance requirements. As examples of this, gypsum boards are used for fire resistance and concrete may be used to achieve thermal mass or acceptable levels of floor vibration [195]. In this regard, the height of the building has a significant effect, since the fire protection requirements become more stringent with increasing number of floors. The higher the fire requirements the more non-combustible material has to be installed in the construction, which results in the positive effects of timber construction with regard to GHG emissions being offset by the use of non-combustible materials [194].

Regarding building height, it is also worth noting that a structural wooden flooring becomes thicker than a construction in concrete to achieve the same functional requirements [179], [407]. This results in fewer stories in taller wooden buildings than in the equivalent with concrete floors, which may disadvantage houses with a wooden frame in regard to restrictions in municipal development plans [407].

An overview of the emission reduction measures and indicated abatement potential described in literature for the supply chain of engineered wood products, with a focus on cross-laminated timber, is provided in Table 9. The baseline assumes sustainable forestry as a prerequisite, while not taking temporary carbon sequestration into account.

Table 9. Overview of emissions reduction measures for engineered wood products described in the literature, together with the described time aspect of implementation (if available). The indicated abatement potential is compared with the average GHG emissions intensity for glulam and cross-laminated timber, assuming sustainable forestry.

Emissions reduction measures	**Reduction potential identified**	**Time of implement-ation**	**Additional references**
Biofuel substitution/electrification in forestry operations	**4%–5%** [391]–[393]	2025/2030–	
Biofuel substitution/electrification (including modal shifts to train) in transport systems	**26%–40%** [391], [393], [399]	2025/2030–	
Use of low-carbon electricity in sawmills and processing plants	**20%–24%** [196], [399], [400]	Present/2025–	
Reduction of the share of resins	**4%–5%** [399], [401], [402]	Present–	
Substitution to natural resins	**16%** [92]	2025/2030–	
Local timber sourcing and use of light wood species	**14%** [393]	Present–	

4.2.9 Windows/glass

Usually, windows are framed with either aluminum or wood, with wood-frame windows having a significantly lower climate impact [408]. For wood-frame windows with metal details, around 60% of the climate impact originates from the glass and around 30% is from the aluminum(or steel), with the remainder being from the wood and manufacturing [92], [102], [121], [408].

Flat glass manufacturing primarily takes place in gas-driven melting furnaces, and 75% of the CO_2 emissions from glass production are linked to the use of natural gas, while the remainder is attributed to electricity use and the release of CO_2 from raw material carbonates [102], [409]. The use of recycled glass, called "cullet", can help to tackle the raw material emissions, as this type of glass requires less energy to melt [174], [409]. Old window glass is mainly recycled in the production of container glass or formed glass. Float glass manufacture requires very pure raw materials and, therefore, there are challenges associated with adding recycled glass to the melt [102], [410]. Nonetheless, recycled glass accounts for about 25% of what goes into European flat glass furnaces [409]. To enable higher levels of recycling, there is a new development for end-of-life buildings that involves glass collection, sorting and recycling, where segregation and other measures are employed to keep the cullet uncontaminated [411].

From an advanced technology perspective, there are innovations to apply preheating and oxyfuel-fired furnaces, which would result in higher quality and productivity and lower furnace energy consumption [412]. Furthermore, electric furnaces already exist, albeit not at the scale of large commercial standard sizes [102], [300], [412].

Using the average embodied GHG emissions intensity of wood frame windows as a baseline, Table 10 provides an overview of the emission reduction measures described in literature together with the indicated abatement potential and expected time of implementation.

Table 10. Overview of emissions reduction measures for wood-frame windows described in the literature, together with the time aspect of implementation (if available). The reduction potential is compared with the average GHG emissions intensity for wood-frame windows with aluminum details, including flat glass manufacturing.

Emissions reduction measures	**Reduction potential identified**	**Time of implement-ation**	**Additional references**
Use of secondary steel/aluminum in window details	**23%–28%** [88]	2025–	
Energy efficiency/process upgrades in flat glass manufacturing	**4%–13%** [412]	2025–	
Electrification of melting furnaces in flat glass manufacturing	**30%** [412] **53%** [102]	2030–	
Recycling of flat glass	**23%** [409]	2025/2030–	

4.2.10 Asphalt production and paving

Asphalt is a mixture of aggregates, binder and filler, used for constructing and maintaining roads, parking areas, airports etc. Aggregates used for asphalt mixtures could be crushed rock, sand, gravel demolished concrete or slags. To be able to provide the best performance to different applications, a large variety of asphalt mixes are used [413]. For heavily trafficked roads, most of these are hot-mix asphalts, which are produced at an average production temperature of between 150 and 180°C [414].

In Sweden, many asphalt plants are being converted to run on biofuels, using for example bio-oil, wood powder or wood pellets [296]. While this conversion confers a clear climate benefit, halving the emissions associated with the asphalt production process, a shortage of suitable and inexpensive biomass resources could hamper its prospects for wider adoption.

We also observe that relying on biofuel conversion as the main asphalt abatement measure carries the risk of increasing the asphalt manufacturing cost if/when other sectors start moving down the same path of biofuel conversions, with increasing competition as a result (as per sector roadmaps, see [161], [180], [313]).

For that reason, it is important to ensure that the focus remains firmly on adopting and scaling up the range of alternative asphalt abatement measures that already exist, including lowered production and paving temperatures, increased recycling rates, and support for additional circularity measures [413], [415].

New asphalt technologies and mixes can reduce the temperatures required to produce and place the material, reducing fuel consumption and GHG emissions [416]. Another key advantage of warm-mix asphalt (WMA) over conventional hot-mix asphalt is the potentially greater use of recycled (or reclaimed) asphalt pavement (RAP), which reduces the need for virgin bitumen binders [413]. Even-lower-temperature asphalt emulsions are currently used on low-traffic roads, and while mixes able to withstand heavier traffic are under development, their potential for wider adoption is uncertain [416], [417].

Other potential options include electrification of quarries for aggregate production [418], [419], the use of secondary materials such as recycled materials as aggregate (e.g., construction and demolition waste and slag from municipal waste incineration to replace natural aggregates [420]), and the introduction of bio-based binders [421]. Regarding the latter, tests are being undertaken of road stretches with binders based on higher levels of lignin, which is the natural resin in wood, lower levels of which have previously been used in The Netherlands [419].

An overview of the emissions reduction measures described in literature for asphalt including the range of indicated abatement potential is shown in Table 11. It is worth noting that the applicability and expected time of implementation for the different emissions reduction measures may depend on its specific application.

Table 11. Overview of emissions reduction measures for bitumen-bound layers described in the literature, together with the described time aspect of implementation (if available). The reduction potential is compared with the average GHG emissions intensity for bitumen-based layers of hot-mix asphalt.

Emission reduction measures	Reduction potential identified		Time of implem-entation	Additional references
Bio-based fuel in asphalt production	**33%** [422] **35%** [296]	**47%** [423]	Present–	[54]
Warm-mix asphalt (WMA)	**5%–12%** [413] **10%** including 40% reclaimed asphalt (RAP) [413] **12%** WMA in base layer with 30% RAP [424]	**15%–16%** [414] **19%** [416]	Present–	
Cold asphalt emulsion mix	**52%** [417] **40%–60%** [413]	**68%** including 40% RAP [416]	2025–	
Asphalt recycling and reuse (RAP)	**10%** WMA with 40% RAP [413] **12%** 20% RAP [416] **13%–24%** 25% RAP [425] **13%–14%** HMA and WMA with 15% RAP [414]	**5%–20%** 50% RAP [426] **16%–25%** 30%–50% RAP [427] **23%–36%** 77% RAP [428]	Present–	[51], [429]
Reduce aggregate moisture content	**1%–5%** [426] **4%–14%** [413]	**9%** [54]	Present–	[420], [430]
Use of other waste products in pavements	**5%** Fly ash [431]	**6%** Blast furnace slag [432]	2025–	[433]
Bio-fueled/electric aggregate production	**2%–3%** [54] **3%** [422]	**6%–7%** [423]	2025/2030–	[419]

4.2.11 Heavy transport systems

Current strategies for reducing the carbon impact of freight (delivering to site and taking materials away from the site) involve: using more-fuel-efficient vehicles; using low-carbon vehicle fuels; reducing the amount of materials moved; reducing the distance traveled; increasing the utilization rate of vehicles and increasing driving efficiency through driver behavior; and speed limiters and/or other engine control units [108], [434]. Improving the logistics of trucking movements also has significant potential in this context [106]. Over the longer term, deeper emissions reductions would result from direct or indirect electrification [75], [105], [435]. Direct electrification with battery-electric trucks, which are already in used in short-distance trucking, could potentially by supported by electric road systems for longer distances [153], [154], while indirect electrification could take the shape of liquid fuels synthesized from hydrogen or fuel-cell trucks driven by hydrogen with the hydrogen in both cases produced via electrolysis [111].

At present, heavy-duty trucks are predominantly driven by internal combustion engines fueled by diesel. Biofuel substitution is, thus, a key short-term emission reduction measure, combined with vehicle efficiency technologies, including hybridization with double power trains, waste heat recovery, and regenerative braking [436], [437].

Regarding biofuel substitution, since 2018, Sweden has been implementing a mandate that initially required at least a 20% share of biofuel in diesel, with policymakers striving to increase the share to 40% in Year 2030 [438], [439]. However, it is worth noting that the sustainability and level of climate change mitigation resulting from biofuels are debated [440]. So far, the production of biofuels for the Swedish transport system has relied heavily on imported raw materials. For the production of hydrogenated vegetable oil (HVO) and fatty acid methyl ester (FAME), which are the main biofuel components for diesel production, over 95% of the raw materials were imported in 2019, with around 50% of HVO produced from palm oil or the palm oil derivative PFAD [441]. Uncertainties surrounding the climate benefits associated with palm oil and PFAD emanating from issues around deforestation and land use change [442]–[446] have led the Swedish government to reclassify PFAD as a co-product rather than as a residue from January 1st 2019 [447], [448], which implies that its GHG emissions intensity factor has been greatly increased [446], [449]. Indeed, the GHG emissions associated with the lifecycles of biofuels vary widely dependent upon fossil fuel inputs and changes in soil and above-ground carbon stocks [148], [450], [451].

Further, previous research has suggested that a shortage of biomass is imminent unless production is ramped up or wood and agricultural products from other uses are directed towards the manufacture of transport and combustion fuels (see [111], [335], [452]). In Sweden, consumption of HVO100 has been growing rapidly from close to zero in 2014 to around 5% of total road transport fuel use in 2017 [441]. However, shortages are already being experienced [446], while demand is expected to continue to increase (e.g., owing to obligations related to biofuel blending [438]). Indeed, while deliveries of HVO100 rose sharply in 2016 and 2017, they decreased slightly in 2018 and decreased significantly in 2019 [453]. Thus, it is by no means clear that the current development of Swedish and EU biofuels policies will enable the supply of levels of biofuels sufficient to reach the demand anticipated by Year 2030 [454].

With the reclassification of PFAD, however, there are signs that biofuels based on Swedish raw materials, mostly residual products from forestry, forest industries, and agriculture, are on the increase, as evidenced by a wave of new pilot and commercial projects for HVO biodiesel [443]. The Swedish oil refinery Preem, for example, has planned a 600% increase in its production capacity, to reach 1.3 million m^3 in 2023 and 5 million m^3 by 2030 [443], [455]. If realized, this would satisfy an estimated 80%–90% of the volume of biofuels required in Sweden to achieve the climate goals in the transport sector [439]. Yet, very few residual materials are subject to any significant rate of disposal without utilization, so there is a risk that increasing the use of those materials for biofuel production will create a supply shortfall for some other use(s), a shortfall that must be met with other materials, which in many cases may have significant emissions implications [442].

To summarize, while transport biofuels have an important role to play in reaching their full climate mitigation potential in the short term, limitations linked to upscaling and the availability of transport biofuels will result in a greater push to speed up the implementation of alternative abatement measures and the deployment of biofuels only where there are no alternatives [74], [75]. This conclusion is also shared by the Swedish Energy Agency, which has reported that the transition to a sustainable society requires a holistic approach that also includes elements other than biofuels, such as transport-efficient community planning and energy-efficient vehicles [453].

In the longer term, deeper reductions in emissions would result from the electrification of heavy trucks. For the latter, the options include fuel-celled or battery-powered electric heavy-duty trucks/haulers, possibly in combination with electric road systems (ERS). Complete electrification with battery-powered electric trucks for short-haul vehicles used in local distribution is already becoming cost-competitive, and several studies have demonstrated that battery-powered electric vehicles for long-haul trucking could also be possible in the mid- to long-term [75], [105], [111], [153], [154]. However, to allow their widespread usage, the road-freight sector would have to transform well beyond the vehicle, to include large-scale infrastructure investments such as a vast, comprehensive rollout of a fast-charging infrastructure and/or ERS infrastructure [105], [454]. If accompanied by power sector decarbonization, road freight electrification would put land freight on a Paris-compliant pathway [153].

Moreover, if current assumptions (mainly with regards to battery prices and performance) are correct, the transition would also be cost-effective for the trucking sector [153], [154].

Sweden, together with Germany, is spearheading a path towards electrification with the support of ERS [454], [456], with the Government of Sweden recently launching four new initiatives towards electrification of the transport system, including a plan for electric roads, an analysis of the charging infrastructure for heavy vehicles along major roads, and the establishment of an Electrification Commission [457].

However, hydrogen and fuel cells can also play important roles in the achievement of a low-carbon road transport system, in particular for long-distance transport [74], [454]. Although hydrogen fuel cell-powered electric trucks are more expensive, the technology is now being pursued on multiple fronts [454], [458], [459].

Modal shifts for heavy transport to rail and ships is another potential abatement measure, although the scope for such modal shifts varies greatly by specific location, mainly depending on the availability and quality of the rail and waterway infrastructures [75], [460]. While most studies rate the potential for modal shifts as a mitigation measure as relatively low, alternatives to road (rail, waterborne transport) could be an important driver towards a more transport-efficient society, if pursued more effectively to realize the potential of multimodal transport and modal shifting [74], [461]. For example, the European Commission has reported that rail freight would need to become more competitive compared to road transport, through eliminating operational and technical barriers between national networks, and by fostering innovation and efficiency [74].

Table 12 provides an overview of the emission reduction measures for heavy transports described in literature together with the indicated abatement potential and described time aspect of implementation. For most of the emissions reduction measures, the indicated abatement potential is compared to transports with heavy trucks. However, for the measures denoted "overall", the indicated abatement potential is for the heavy transport system. As can be seen, there is a wide range in the indicated abatement potential for several of the emissions reduction measures, particularly regarding biofuel substitution and electrification measures. For the former, this mainly relates to the raw material sources used in the production of biofuels, while for the latter it partly relates to the level of electric penetration and partly to the GHG emissions intensity factor of the electricity used.

Table 12. Overview of emissions reduction measures for heavy transport described in the literature, together with the time aspect of implementation. The emissions reduction measures are related to heavy transport units (trucks and on-road haulers) except for the measures denoted "overall", where the indicated abatement potential is related to the heavy transport system. For the measures related to heavy transport units, the reduction potential is compared with the average GHG emissions intensity based on the reference energy use of a 32-tonne Euro 6 truck.

Emission reduction measures	Reduction potential identified		Time of implement-ation	Additional references
Optimization of logistics and road freight operations	**15%** [462] **15%–20%** [75] **17%** [153]	**20%** [105] **10%–33%** [106]	Present–	[74]
Shifts to biofuels in heavy transport units	**83%** HVO100 well-to-tank compared to Diesel MK1 [441] **36%–90%** HVO well-to-tank from various sources compared to fossil diesel [452]	**66-90%** HVO well-to-tank from various sources compared to fossil diesel [463]	Present–	[105], [106], [454]
Vehicle energy efficiency optimization	**6%–19%** [464] **7%–17%** [436]	**16%** [465] **11%–22%** [466]	2025–	
Hybridization of heavy transports (double power trains)	**31%** [467] **33%** [468]		2030–	[105], [437], [466], [469]
Road freight electrification (overall, including electric road systems, ERS)	**5%–22%**; to 2050 [74] **30%**; to 2050 [435] **40%–50%** [454] **50%** [105]	**50%**; ERS to 2040 [105] **60%**; ERS **42%–72%**; Battery-electric [153]	2045–	[111]
Fuel-celled or battery-electric heavy vehicle	**27%–39%** [470] **70%** [468]	**90%** [469]	2030–	[75], [106], [154]
Modal shift (overall)	**3%–5%** [106] **2%–10%** [74]	**13%** [75]	2025/2030–	[471]

4.2.12 Construction process

Generation of waste, together with use of fossil fuels for heavy equipment and the transportation of building materials are considered the most common emissions sources during the construction stage [11], [40], [197]. The construction activities include earthwork and concrete works, the use of cranes to erect the frame and move materials around the construction site, construction lifts and internal transports onsite [13], [179].

Other emissions sources include the electricity and heating consumed by power tools and temporary lighting, together with construction and office sheds [11], [40], [434]. In addition, drying processes are sometimes accelerated by the use of diesel units or electric dryers to reduce time and costs for the projects [121], [179].

Like heavy trucks, construction machinery (dump trucks, excavators, etc.) are predominantly powered by diesel. Thus, as described above in Section 4.2.11, the main abatement technical measures for the various items of construction machinery are fuel substitution, hybridization, and eventually electrification [107], [109], [110].

Hybrid excavators and wheel loaders are already available on the market along with a few examples of electric machines [472], [473], and the development towards electrification is expected to continue [91], [474]. However, their wider adoption would require collective agreements or incentive structures that cascade requirements down the supply chain, so as to assure construction equipment owners that investments in machinery with higher upfront costs will repay themselves [91], [475]. As an example, the City of Oslo in Norway is using public procurement to support this change, by setting procurement requirements and ambitious, predictable targets for the reduction of emissions from construction sites [476].

The City of Gothenburg in Sweden is also following suit with the development of recommendations for procurement requirements aiming to accelerate the construction sector's transition to emission-free construction sites [477]

Non-technical abatement measures include increased levels of prefabrication, combined with optimization of mass and material handling requirements and optimization of the site layout, utilization of vehicles, speeds and routes, and the choice of vehicles for the intended use [13], [50], [107], [108].

Other abatement measures include the use of energy-efficient site cabins as temporary offices and sheds on construction sites, which often lack building management controls and are poorly insulated [179], [434]. For some construction sites, CO_2 emissions can also be reduced by connecting the site to the electricity grid more rapidly, as this minimizes the amount of diesel used to power generators [434].

An overview of the emission reduction measures for various construction activities and equipment described in literature together with the indicated abatement potential is provided in Table 13.

Table 13. Overview of emission reductions measures for construction activities described in the literature, together with the time aspect of implementation (if available). The reduction potential is compared with the GHG emissions intensity based on the reference energy use and energy source of the specific construction equipment/activity.

Emission reduction measures	Reduction potential identified		Time of implem-entation	Additional references
Optimization of material handling/ equipment use	**4%–13%** [478] **10%** [107] **12%** [479]	**17%** [480] **21%** [481]	Present–	[482]
Shifts to biofuel use in construction equipment	**86%** HVO 2017 well-to-tank vs Diesel MK1 [463] **36%–90%** HVO well-to-tank vs fossil diesel [452]	**66%–90%** HVO well-to-tank from various sources vs fossil diesel [463]	Present–	[107], [110], [483], [484]
Hybridization of construction equipment	**15%–25%** General [107] **13%–26%** Excavators [485] **15%** Excavators [486] **25%–40%** Excavators [107] **21%–41%** Excavators [487]	**10%–35%** Wheel loaders [107] **20%–50%** Wheel loader [478] **30%** Wheel loader [488]	Present/ 2025–	[110]
Fuel-celled/plug-in hybrid construction equipment	**50%** [488] **56%–59%** [489]	**60%** Supercapacitor and batteries [487]	2030–	[107], [110], [478]
Electrified construction equipment	**67%** Energy efficiency [490] **95%** [472]	**95%** [475]	2030/2045	[110], [491]
Bio-fueled electric rock crushing plants	**17%** Bio-fueled [480] **94-97%** Electric [492] **91-97%** Electric [481]	**91%** Electric [493] **95%** Electric [52]	Present/2025 –	[475]
Work shed/office efficiency	**7%–9%** [179]	**7%–10%** [367]	Present–	[98]

5 Summary of results and discussion

From the results presented in **Papers I–III**, it can be concluded that it is possible to reduce the embodied GHG emissions significantly in the construction of buildings and transport infrastructure already with currently available technologies and practices. The results also demonstrate the potential to reach close-to-zero embodied GHG emissions by Year 2045, given the electrification of construction equipment and the heavy transport system as well as transformation of basic material industries towards the implementation of carbon capture and/or electrification. Figure 4 gives a summary of the results for the respective scenario for the road construction and building cases demonstrating the highest potentials for reductions in embodied GHG emissions. The figure also indicates the types of abatement measures that contribute to the emissions reductions.

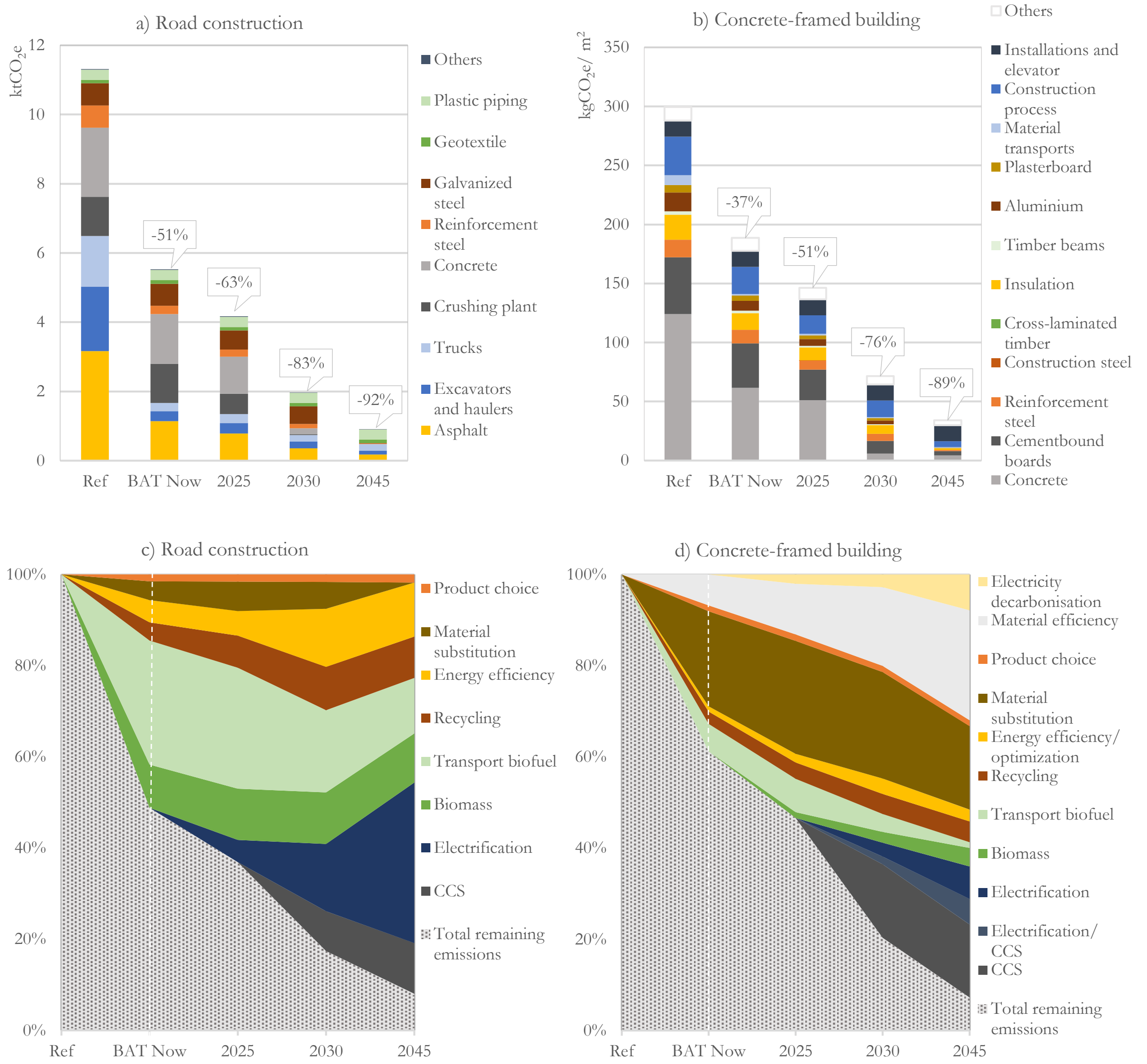

Figure 4. Summary graphs depicting the results from the case studies in ***Papers I*** *and* ***II.*** *Shown are the overall embodied GHG emissions potentials for a road construction case and a concrete-frame multi-family building system, respectively, with best-available technologies and practices (BAT Now) and over time until Year 2045 (a and b), and the types of abatement measures contributing to the GHG emissions reductions over time in the road construction and building cases, respectively (c and d). Note that no GHG emissions reduction analysis has been performed on geotextiles and plastic piping in the road construction case, and similarly no GHG emissions reduction analysis has been performed on installations and elevators in the building case.*

The results in **Paper I** indicate that it is possible to halve the embodied GHG emissions associated with a road construction project already at present, with more than half of the current emissions reduction potential arising from substituting diesel use with transport biofuel use. This would require sufficient availability of sustainably produced second-generation drop-in biofuels (e.g., hydrogenated vegetable oil, HVO). On the one hand, the use of biofuels in the transport and industrial sectors is a clear prerequisite for successful decarbonization, whereas on the other hand, there are limits to the available supply of truly sustainable biomass.

As indicated in Section 4.1.2, given the increased value of biomass with increased deployment and its likely limitation of supply, the willingness to pay for the biomass could, and feasibly should, limit its use in sectors where alternatives exist [75].

Thus, while transport biofuels have a substantial role to play in reaching the full climate mitigation potential in the short term, more effort is needed to speed up the implementation of alternative abatement measures that involve optimization of materials, design, mass handling and transport systems, as well as the use of alternative materials and designs.

When applying current best-available technologies and practices along the supply chain in the building study in **Paper II**, we see potential reductions in embodied GHG emissions of close to 40%. More than half of that reduction is attributable to optimized concrete recipes that reduce the amount of cement combined with cement clinker substitution in concrete and other cement-based products. Applying material efficiency measures to slim the construction contributes with another fifth of the GHG emissions reduction, with additional abatement actions resulting from the optimization of logistics and equipment use, the use of transport biofuels in heavy vehicles, and the use of recycled feedstocks in plasterboard, steel and aluminum production processes.

We note that in order to realize the potential of applying abatement measures across the supply chain, there is a need for more extensive collaboration along the whole value chain. Taking the example of concrete, to realize the potential of a combination of cement clinker substitution, optimization of concrete recipes and slimming of structural elements, close collaboration between all the relevant actors in the supply chain, including cement producers, concrete producers, structural engineers, procurers, clients, and architects, needs to be initiated already during the design and early procurement phases, with close communication continuing throughout the planning and construction phases [113]. This also implies that demand-side actors within the value chain, such as investors, developers and designers, work together with those on the supply side – the contractors and materials manufacturers. While material efficiency measures would reduce material costs, they are associated with larger intangible costs linked to the complexity and implications associated with their implementation [494], [495]. For these types of collaborations to take place, the incentives must be changed, including the procurement requirements and contract forms that enable balanced risk sharing and involve contractors early in the planning and design processes [496], [497]. This must happen in parallel with strong policy and regulatory support initiatives, access to finance, and measures that promote risk distribution along the value chains [8], [101], [498].

On a national level, the results in **Paper III** show that it is possible to reduce CO_2 emissions associated with the construction of buildings and transport infrastructure by 50% up to Year 2030 by applying already available measures, and to reach close-to-zero emissions by Year 2045. The latter would require comprehensive measures across-the-board, including breakthrough technologies for heavy vehicles, construction machinery and for cement and steel production processes. Several key opportunities and obstacles for the realization of breakthrough technologies for basic industry are highlighted – including carbon capture with or without electrification for cement production and hydrogen-reduced iron for primary steel production (with hydrogen produced by electrolysis), supported by the electrification of construction equipment and heavy transport. That electrification and carbon capture are important for reaching near-zero emissions up to Year 2045 is evident in Figure 4, c and d for the road and building construction cases, respectively). The scenario analysis of the building study presented in **Paper II** demonstrates that if the abatement focus is limited to primary material production, over half of the total abatement to Year 2045 will be attributable to electrification and CCS, while this share goes down to around 30% if implementing material efficiency measures across the supply chain. Nonetheless, electrification and carbon capture are critical for reaching the set goal of net-zero GHG emissions by Year 2045.

The work included in this thesis, in alignment with previous analyses (as reported by, for example, Gerres et al. [34]), demonstrates the importance of ensuring sufficient availability of sustainable biomass/bioenergy, electricity and hydrogen. That the upscaling of these energy sources is an urgent priority becomes particularly evident as experience shows that planning, obtaining permits and construction of both the support infrastructure (RES energy supply, electricity grid expansion, hydrogen storage, CCS infrastructure) and the piloting and upscaling to commercial scale of the actual production involve long lead times. Therefore, strategic planning for key support infrastructure needs to be initiated as early as possible, even if not all the uncertainties are fully resolved at that time-point. Furthermore, in a carbon- constrained world in which all sectors of the economy seek to lower emissions, competition for energy carriers that have a weak climate impact (biomass/biofuels, green electricity and hydrogen) will grow. As a consequence, the ways in which integration, interlinkages and interactions across sectors are handled will crucial to the overall outcome [151].

One of the key messages from this work is the importance of not letting the pursuit of 'low-hanging fruits' (e.g., material substitution and efficiency measures) become an excuse for not acting to lay the foundation for the high-cost, long lead-time measures (zero-CO_2 basic materials) that will be required for decarbonization.

Conversely, it is vital not to allow the promise of, for example, low-CO_2 steel or cement become an excuse for not acting to unlock the potentials of measures that already exist today. Indeed, studies have found that delaying the peaking of emissions drastically increases the mitigation challenges, in terms of the technology upscaling requirements, stranded assets, and medium to long-term mitigation costs for climate stabilization [499].

We see a clear need to prepare for deeper abatement and associated transformative shifts already now. It is vital to consider carefully the pathway while avoiding pitfalls along the way, such as over-reliance on biofuels or cost optimizations that cannot be scaled up to the levels required.

Successful decarbonization of the supply chains for buildings and infrastructure, including the production of basic materials, will involve the pursuit - in parallel - of emission abatement measures that have very different characteristics (as illustrated in Figure 5). To facilitate the transition, the support tools box will need to contain a variety of policies and strategies. As a wide range of instruments regulate GHG emissions from building and construction, a combination of different policies is needed to address the different technological development stages, types of abatement options, and decision modes of actors that are in a position to contribute to the decarbonization of buildings and transport infrastructure [156], [500]–[502].

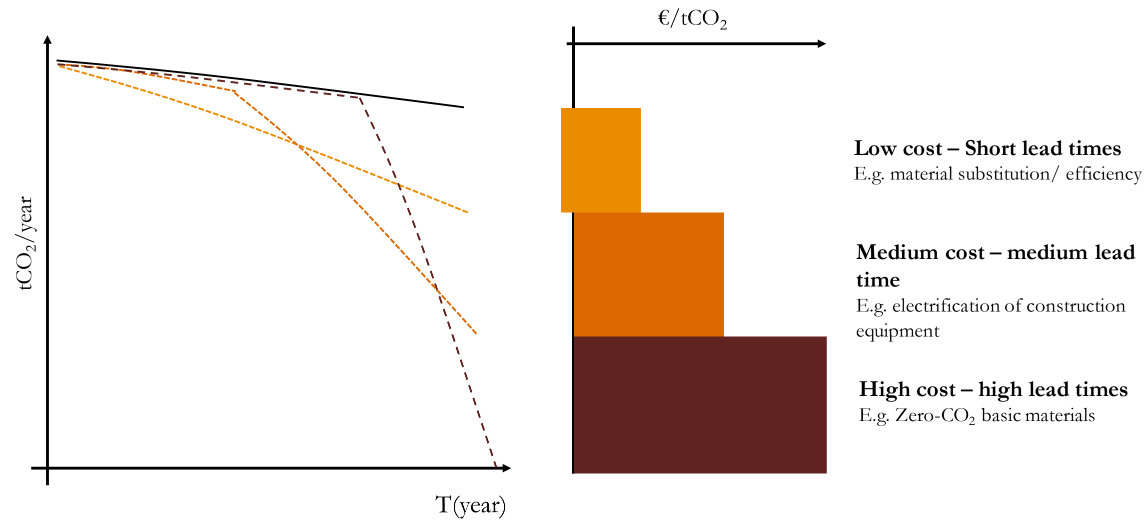

Figure 5. Successful decarbonization of the supply chains for buildings and infrastructure during a period of less than three decades will require the simultaneous pursuit of emission abatement measures with very different characteristics. Figure adapted from Vogt-Schilb and Hallegatte [503].

Therefore, unlocking the full abatement potential of the range of emission abatement measures investigated in this work will require not only technological innovation, but also innovations in the policy arena and efforts to develop new ways of co-operating, coordinating and sharing information between actors in the supply chain. Details of the risks, uncertainties and enabling actions expressed by the stakeholders through the participatory process of Mistra Carbon Exit are provided in three technical reports closely linked to this thesis work [67]–[69]. The key priorities include:

- **Providing policy coordination** and clear responsibility for monitoring and follow-up of progress.
- **Continued support for hybridization and electrification** of heavy transport and construction equipment.
- **Using public procurement** as a tool to spur innovation, creating markets for low-CO_2 products and opening up for economies of scale.
- **Capacity building** and information spreading.
- **Development of an integrated industrial climate strategy**, including adaptation of legislation, and innovative schemes to share the risks and costs associated with developing and implementing new process technologies and infrastructures (see, for example, [500], [504]).
- **Strategic planning for support infrastructure**, including that for electricity transmission, hydrogen, carbon transport and storage, and sustainably sourced biomass/biofuels.

Although the findings reported in this thesis work draw primarily on Swedish experiences and some of the conclusions are valid only for certain conditions and circumstances, many of the challenges that have been considered here, and that must be overcome if one is to achieve the transition to zero-CO_2 production and practices in the supply chains for buildings and infrastructure, are universal [8], [21], [23]. Whereas rapid improvements to the climate performance of the use phase (i.e., related to heating and cooling) of the existing and new building stocks are a key priority in many parts of the world, it is equally important to take measures to reduce the climate impacts of the construction process and the production and supply of building materials.

Finally, to support effective climate-change mitigation, embodied GHG emissions must be 'carbon-effective' and respect limited carbon budgets [10]. The measures proposed in this work, therefore, could (and perhaps should) also be backed by strategies that avoid building through exploring alternatives and that act to repurpose assets and reducing the floor area per capita with smarter floor plans and increased use of shared spaces. After all, reducing the square meters or kilometers built is still the most effective way to reduce both embodied and operational GHG emissions [38,43,158].

6 Future research

As discussed in **Paper III**, current best estimates of the impacts on climate of building and construction processes in Sweden are associated with a significant degree of uncertainty. While the analysis performed in **Paper III** serves to improve the current estimate, there remain significant deficiencies associated with the methods used to assess the climate impact from construction in Sweden.

This is partly related to a lack of relevant data, for example regarding the total use and composition of different steel-, concrete-, and other cement-based products. To provide well-grounded decision support for the climate transition ahead, it is important that the development of embodied GHG emissions be properly evaluated, so that the effects of planned measures and policies can be assessed before implementation. It would, therefore, be relevant to develop a bottom-up stock model for tracking material flows and related GHG emissions along the supply chain related to building and infrastructure construction in Sweden.

As noted in this work, the different options for deep decarbonization have different characteristics. On the one hand, material efficiency measures, while reducing material costs, are associated with larger intangible costs [494], [495]. On the other hand, transformative technologies, such as application of CCS in cement clinker production and electrification of primary steel production, are characterized by high investment costs [111], [157], [300]. To obtain a better indication of how these costs impact the end-user and how the cost structure would look like along the value chain, further analysis is needed. Building on previous work conducted by Rootzén and Johnsson (2016, 2017) [120], [505] for cement and steel, it would be useful to develop and propose a framework for analyses of the supply chain and end-user abatement cost implications. This might be undertaken in parallel with the implementation of a specific case project.

Although there are limitations to the scope of the analysis, no scenario in the different studies reaches zero carbon emissions. Therefore, it is important to investigate further the potential for and accounting of negative emissions (e.g., carbon capture of biogenic emission) and carbon sinks (e.g., use of long-lived wood products in construction), so as to enable an approach towards net-zero emissions by Year 2045.

Another area of interest is the impact associated with the location of the construction site. The combination of population growth and urbanization incentivizes the construction of more densely concentrated urban areas [506], where the lack of easily constructed land lots often leads to the requirement for considerable earthwork excavation and support foundations [507]. As noted in **Paper II**, most LCAs of buildings do not include emissions associated with the groundwork or soil stabilization needed to prepare the construction site. Studies that do include the carbon footprint of machinery during the foundation-creation phase indicate that these emissions can be significant [91], and researchers have also found that the environmental impacts associated with construction activities are often underestimated [508]. It would, thus, be interesting to investigate further the impact of embodied GHG emissions linked to the location of a building construction site, along with the potential for reducing these emissions. When there is a choice between a construction site in the city center and in a suburban area, requiring different levels of earthwork and soil stabilization, the location of a building also significantly affects infrastructure needs and the transportation demands of its inhabitants [509].

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